The AMERICAN PHYSICS TEACHER

VOLUME 6 OCTOBER, 1938 NUMBER 5

A Survey of Piezoelectricity

WALTER G. CADY
Department of Physics, Wesleyan University, Middletown, Connecticut

THE discovery of a new "effect" relating different classes of physical phenomena is always a stimulus to research, sometimes with far-reaching results in the form of fundamental theory, and with important technical applications as by-products. Outstanding examples are Oersted's discovery of the magnetic effect of an electric current, the equivalence of heat and mechanical work, and the various relations between electricity and radiation. Many other instances might be mentioned, including the various thermoelectric effects, the Kerr and Faraday effects, pyroelectricity, electrostriction, and magnetostriction.

Among these relationships is that between electrostatics and mechanics, discovered in certain crystals by the brothers Pierre and Jacques Curie[1] in 1880. On this phenomenon the name *piezoelectricity* was soon bestowed by Hankel.[2]

One may define piezoelectricity as *the production of electric polarization by mechanical strain in certain crystals, the polarization being proportional to the strain and changing sign with it.* This statement defines the *direct piezoelectric effect.* Closely related to it is the reciprocal or *converse effect*, whereby a piezoelectric crystal becomes strained when in an electric field.

2. The existence and magnitude of the *converse effect* were predicted by Lippmann[3] from the principle of conservation of energy. His reasoning may be expressed in the following manner. A piezoelectric crystal is placed in an electric field of strength E and at the same time subjected to a mechanical stress X. There are then present in the crystal an electric polarization P and a strain x. If now the two stresses, electric and elastic, are varied by small amounts dE and dX, the total change in energy dU may be expressed as an exact differential, $dU = PdE - xdX$. (The negative sign is due to the rather unfortunate convention whereby a stress is called positive when it causes a negative strain.) Then, just as in the case of the analogous equation in thermodynamics, assuming the process to be reversible, we may write

$$(\partial P/\partial X)_{E=\text{const}} = -(\partial x/\partial E)_{X=\text{const}}. \qquad (1)$$

This equation tells nothing concerning the law of dependence of P upon X. It is found *experimentally*, over very wide ranges of pressure, that the relation is linear with almost all crystals that have been tested. We therefore write $\partial P/\partial X = \delta$, where δ is the *piezoelectric strain-constant.* The case of such crystals as Rochelle salt, in which δ is a function of the stress, will be considered later. The expression $\partial P/\partial X$ obviously represents the direct effect, and Eq. (1) says that there is a converse effect, $\partial x/\partial E$, having the same constant δ with sign reversed. This prediction was confirmed in the case of quartz, both

[1] P. Curie, *Oeuvres de Pierre Curie* (Paris, 1908); Comptes rendus **91**, 294 (1880).

[2] The statement is still sometimes made that certain electric effects observed with crystals in the early part of the 19th century were in fact piezoelectric. Careful perusal of the original publications, however, leads to the conclusion that these effects were due to contact rather than to strain.

[3] G. Lippmann, J. de phys. **10**, 381–394 (1881).

BOSTON UNIVERSITY
COLLEGE OF LIBERAL ARTS
LIBRARY

qualitatively and quantitatively, by the Curies in 1881. There is little doubt of its general validity, unless perhaps quantitatively in such substances as Rochelle salt, wherein the piezoelectric process is not strictly reversible.

3. Piezoelectricity in artificial substances. There are certain artificial waxes and other non-crystalline substances in which the piezoelectric effect is said to have been found. We are not concerned with them in this survey beyond remarking that such effects, insofar as they may properly be called piezoelectric at all, are due either to minute piezoelectric crystals imbedded in the wax, or to polarization produced by letting the substance harden while in an electric field.

4. Electrostriction and pyroelectricity. At this point we consider the distinction between piezoelectricity, pyroelectricity, and electrostriction.[4] *Electrostriction* differs from the converse piezoelectric effect in that it is a property common to all substances—solid, liquid, or gaseous; it is dependent on the square of the field and hence independent of the direction of the field; and in magnitude it is extremely minute, small even in comparison with the piezoelectric effect in most crystals. Hence, in most piezoelectric investigations it can be completely ignored.

The *pyroelectric effect* is a crystal phenomenon dependent upon certain conditions of symmetry, and it may exist in crystals belonging to ten classes, all of which are also piezoelectric. In all cases it owes its existence to the presence of a *permanent spontaneous polarization* which is inherent in the crystal and is the electrostatic analog of permanent magnetism. Under ordinary conditions the spontaneous polarization of itself has no external manifestation, since the polarization surface charges, even in a freshly broken crystal, soon become neutralized by compensating charges through the effects of surface and body leakage. However, since in general the polarization varies with temperature, any thermal change is accompanied by a slight alteration in the positive and negative surface charges, which may be detected until compensation has again taken place. This is the phenomenon commonly described as the pyroelectric effect. It is usually of small magnitude and is seriously complicated by the fact that, whenever the temperature is varied, a piezoelectric polarization always arises from the change in dimensions of the specimen.

If a pyroelectric crystal is *uniformly* heated, the change in dimensions causes a resultant piezoelectric polarization which adds itself to whatever polarization there may be of purely pyroelectric origin. Voigt calls the former a "false" pyroelectric effect and computes that for tourmaline it accounts for four-fifths of the total observed effect. It seems to the writer that the two effects are both so intimately related that there is not much point in discriminating between them. Their combined action might well be called the "genuine" pyroelectric effect, to distinguish it from the quite spurious effect that is caused by *non-uniform* heating.

This latter type of heating (or cooling) will give rise to an electric polarization with *any* piezoelectric crystal, whether or not it belongs to a pyroelectric class. It is for this reason that in the literature the pyroelectric property has been ascribed so often to many crystals that are not genuinely pyroelectric. Quartz may be mentioned as a conspicuous example.

5. Crystal axes and cuts. Crystal axes as defined by the crystallographer are not always at right angles. In describing physical phenomena, however, it is much more convenient to use in all cases the orthogonal crystallographic axes as defined by Voigt and summarized in the ICT.[4] It suffices here to state that the x-, y-, z-axes for the orthorhombic system coincide respectively with the a-, b-, c-axes of the crystallographer, while for quartz (SiO_2, trigonal holoaxial, or trapezohedral) the axes are as shown in Fig. 1. Either end of the z-axis may be taken as positive. The y-axis is normal to the prismatic faces m, its positive end being on the side where there is a pyramidal r-face. Since there are three r-faces, there are three y-axes, and in cutting plates it is a matter of indifference which is chosen. The three x-axes bisect the angles between adjacent

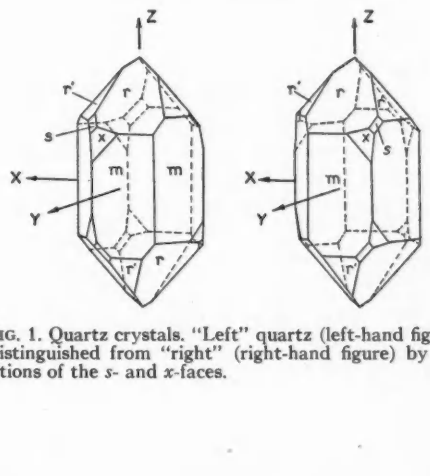


FIG. 1. Quartz crystals. "Left" quartz (left-hand figure) is distinguished from "right" (right-hand figure) by the positions of the s- and x-faces.

[4] *International Critical Tables* (McGraw-Hill, 1929), vol. 6, pp. 207–212.

prismatic faces, their positive directions being such in each case as to form a right-handed orthogonal system with y and z. The r-faces form the "primary positive first-order rhombohedron" and are usually much more fully developed than the r' rhombohedral faces. In a right quartz the positive ends of the x-axes emerge at edges where the s- and x-faces occur. In a left quartz the s- and x-faces are at the *negative* ends of the x-axes. The x-axes are the crystallographic binary or digonal axes, also called the "electric" axes, while the y-axes have sometimes been termed the "mechanical" axes.

If a plate is to be cut normal to one of the axes, it is usually unnecessary to consider whether the crystal is right or left. In any case, if the r-, s-, and x-faces cannot be identified, optical tests will identify the z-axis and also tell whether the crystal is right or left, as well as reveal traces of twinning. Twinned regions are for most purposes to be avoided. The positive direction of an x-axis can then be identified by the rule that, for both right and left crystals, the negative charge, on compression, comes at that end of the axis where the s- and x-faces would be found.

Oblique cuts of quartz are frequently used, and it is for their proper orientation that it is essential to know the positive ends of the x-axes. This is because the elastic and piezoelectric constants assume different values as the direction in the crystal is varied; and, for a given angle of obliquity in any plane containing the z-axis, these constants have different values according to whether the angle is positive or negative.

The *cut* of a plate or bar is a term that has come into general use to designate the orientation of the smallest dimension; this is usually the direction in which the electric field is to be applied. Thus an X-cut means a plate or bar with thickness parallel to an x-axis. Oblique cuts are named by reference to the transformed axes (Secs. 8, 10), as Y′-cut, etc., or else are given a special designation, for example, the AT-cut.

6. Voigt's phenomenological theory. In order for a crystal to be piezoelectric there must be a certain "one-wayness" in its structure; otherwise there could be nothing to determine the sign of the electric polarization when the crystal was strained, for elastic strains and stresses are *tensors* and are centrosymmetrical. A body in equilibrium under stress is subject to *pairs* of forces which are equal in magnitude and opposite in direction; hence, in the nature of an elastic stress, there is nothing that can determine which shall be the positive direction of an electric field. The deciding factor can only be the crystal structure itself, the characteristic in question being the possession of certain "polar axes."

Since electric field strengths and polarizations are vector quantities, it may be said that the mathematical theory of piezoelectricity is a special case of that branch of crystal physics treating of the relations between tensors and vectors. This is indeed the method adopted by Voigt,[5] and by its use he determined which of the 32 crystal classes can be piezoelectric, and for each of them he showed along which of the three orthogonal crystallographic axes components of polarization are found on application of any given stress. These classes comprise 20 of the 21 classes devoid of a center of symmetry.

7. Molecular theory. The theory of Voigt correlates piezoelectricity with geometrical properties in accordance with Neumann's law of correspondence between crystal form and physical characteristics. In a *molecular* theory the attempt is made to explain the ultimate nature of the process by making assumptions concerning the arrangement of smallest particles and the forces between them. Speculative beginnings were made by the Curies, Riecke, and especially Lord Kelvin. A more quantitative theory was offered by Schrödinger in 1913. The most complete treatment thus far is that of Born,[6] who derived from his theory of the equilibrium energy of the crystal lattice, the relation between the dielectric, elastic, and piezoelectric constants for diatomic cubic crystals. He applied the results of his analysis to zinc blende (ZnS) and derived for the constant ϵ_{14} (Sec. 10) the value -2.30×10^5; the most recently observed value is -4.2×10^4. If we consider the very incomplete state of our knowledge of interatomic forces, this agreement is as good as can be expected.

X-ray analysis has thrown considerable light

[5] W. Voigt, *Lehrbuch der Kristallphysik* (Leipzig, Teubner, 1910 or ed. 2, 1928).

[6] M. Born, *Atomtheorie des festen Zustandes* (ed. 2, Leipzig, 1923); *Problems of Atomic Dynamics* (Cambridge, Mass., 1926).

on the arrangement of atoms in quartz.[7] It has been suggested that the distortion of triangular groups of silicon and oxygen atoms under pressure offers a qualitative explanation of piezoelectric polarization in quartz.

Fundamental equations and the piezoelectric constants

8. Elastic and electric stress and strain. The first of the six well-known equations for mechanical stress in terms of strain in anisotropic bodies is

$$-X_x=c_{11}x_x+c_{12}y_y+c_{13}z_z+c_{14}y_z+c_{15}z_x+c_{16}x_y. \quad (2)$$

Five similar equations give the other stress components. X_x and x_x represent stress and strain components parallel to the x-axis. X_x is positive when compressional; positive x_x means an extension. The symbol y_z represents the component of shear in the yz-plane, which may also be described as a shear about the x-axis. The c's are the elastic constants, or stiffness coefficients. Since $c_{12}=c_{21}$, etc., there are, in all, 21 possible independent values of the c's. In only one of the 32 crystal classes do all of these c's differ from zero. In the remaining classes the number of constants differing from zero becomes less and less as the symmetry increases from one class to another.

Similarly, the first of the six equations for strain in terms of stress is

$$-x_x=s_{11}X_x+s_{12}Y_y+s_{13}Z_z+s_{14}Y_z+s_{15}Z_x+s_{16}X_y, \quad (3)$$

where the s's are the compliance coefficients. Each of the 21 independent s's can be expressed as a function of the c's, and *vice versa*.

The elastic constants of obliquely cut crystals can be found by applying the well-known formulas for transformation of axes to a new system designated as X', Y', Z'.

Since we are dealing with relations between elastic and electric phenomena, it is necessary next to write the *electrostatic* expression analogous to Eq. (3). A similar analogy to Eq. (2) could be written, but it will not be needed. What to take as the electric stress and strain is to some extent a matter of choice. In any case, it would not be possible to establish complete symmetry in the piezoelectric equations owing to the essentially different natures of the elastic and electric quantities and the conditions at boundaries. It is customary to regard the electric field strength E in the dielectric as the electric stress, and the polarization P as the corresponding strain.

9. In crystals, the *dielectric susceptibility* η (which is in general related to the dielectric constant k by the equation $k=1+4\pi\eta$) has different values in different directions, denoted by subscripts as in the case of the elastic constants. Moreover, in crystals the polarization is not always parallel to the field. In the general case, therefore, the components of polarization P_x, P_y, P_z have to be expressed in terms of the three field components E_x, E_y, E_z. The first of the three equations is

$$P_x=\eta_{11}E_x+\eta_{12}E_y+\eta_{13}E_z. \quad (4)$$

Fortunately, in all important applications the polarization is at least approximately parallel to the field, whence we may drop the subscripts and write simply, for any direction of field,

$$P=\eta E. \quad (5)$$

We shall have occasion also to write Eqs. (2) and (3) in abbreviated form without subscripts, but with the understanding that in any practical case the proper subscripts must be introduced; thus,

$$-X=cx, \quad (6) \qquad -x=sX, \quad (7)$$

where X and x respresent *any* stress and strain.

In most piezoelectric investigations, as well as in practical applications, the crystal specimen is prepared by cutting from the mother crystal, after careful optical examination to guard against twinning and other defects, either a flat plate of considerable area or a bar of comparatively small lateral dimensions. The electric field is sufficiently homogeneous in either case, and the elastic conditions are greatly simplified. Other geometrical forms, especially that of a ring, are used in special cases.

10. Fundamental piezoelectric equations. Since there are six components of stress and three of electric field strength, it follows that there are

[7] R. B. Sosman, *The Properties of Silica* (Chemical Catalog Co., New York, 1927.

18 possible piezoelectric constants relating the elastic to the electric quantities. For example, when a known stress is applied to a plate or bar, its components are inserted in Eqs. (8) below; and, if the δ's are known, the components of polarization can be computed; or the δ's may be calculated after the P's have been measured. In Eq. (8) we have the fundamental equations for the *direct* piezoelectric effect,

$$\begin{aligned} -P_x &= \delta_{11}X_x + \delta_{12}Y_y + \cdots + \delta_{16}X_y, \\ -P_y &= \delta_{21}X_x + \delta_{22}Y_y + \cdots + \delta_{26}X_y, \\ -P_z &= \delta_{31}X_x + \delta_{32}Y_y + \cdots + \delta_{36}X_y. \end{aligned} \tag{8}$$

The 18 δ's are often called the *piezoelectric moduli*.

It is often desirable to express the P's in terms of strains. For this purpose we introduce the 18 quantities which are called the *piezoelectric constants*, denoted by ϵ. They occupy a position analogous to the elastic c's, while the δ's are more nearly analogous to the elastic coefficients s. Each ϵ is a function of certain δ's and c's, and is therefore a constant of the material. It would be logical to call the δ's and ϵ's the piezoelectric strain- and stress-coefficients, respectively. However, in the literature one frequently finds both δ and ϵ referred to as "piezoelectric constants," the symbol itself specifying which type of constant is meant.

The first of the three equations for the components of polarization in terms of strain is

$$P_x = \epsilon_{11}x_x + \epsilon_{12}y_y + \cdots + \epsilon_{16}x_y. \tag{9}$$

Eqs. (8) and (9) give the *total* polarization only when the field in the crystal is zero. Otherwise they give the piezoelectric contribution toward the total polarization.

The converse effect is expressed by the following two sets of six equations each:

$$\left.\begin{aligned} -X_x &= \epsilon_{11}E_x + \epsilon_{21}E_y + \epsilon_{31}E_z, \\ &\cdots\cdots\cdots \\ -X_y &= \epsilon_{16}E_x + \epsilon_{26}E_y + \epsilon_{36}E_z; \end{aligned}\right\} (10)$$

$$\left.\begin{aligned} x_x &= \delta_{11}E_x + \delta_{21}E_y + \delta_{31}E_z, \\ &\cdots\cdots\cdots \\ x_y &= \delta_{16}E_x + \delta_{26}E_y + \delta_{36}E_z. \end{aligned}\right\} (11)$$

These equations give the *total* stress and strain only when no external stress is applied. Otherwise they give the piezoelectric components of stress and strain.

	x_x	y_y	z_z	y_z	z_x	x_y
E_x	L	T	T	L'	T'	T'
E_y	T	L	T	T'	L'	T'
E_z	T	T	L	T'	T'	L'

FIG. 2. Piezoelectric effects in tabular form.

It will be observed that, with both the δ's and the ϵ's, the first figure in the subscript indicates the direction of the field or polarization, while the second expresses the type of strain. In general, it is not true, as in the case of the elastic constants, that $\delta_{12}=\delta_{21}$, etc. For example, if δ_{24} has a value different from zero, it means that an electric field parallel to y is associated with a shear in the yz-plane. Whenever any δ equals zero, the corresponding ϵ also necessarily vanishes, and *vice versa*.

Figure 2 shows in tabular form, corresponding to Eqs. (11), the nature of the 18 possible "effects," which are of four different types. The symbol L signifies the *longitudinal effect*, in which there is an extension in the same direction as the field (or polarization); T is the *transverse effect*, characterized by an extension at right angles to the field; L' may be termed the *longitudinal shear effect*, with the axis of shear parallel to the field; while T' is the *transverse shear effect*, having the axis of shear at right angles to the field. In Rochelle salt, for example, all three of the L' shear effects are present (δ_{14}, δ_{25} and δ_{36}) and no others. Quartz has only $\delta_{11}(L)$, $\delta_{12}=-\delta_{11}(T)$, $\delta_{14}(L')$, $\delta_{25}=-\delta_{14}(L')$ and $\delta_{26}=-2\delta_{11}(T')$. Thus, although there are in quartz five different effects, the symmetry of crystals in this class is such that only two of the constants have independent values. Tourmaline has eight constants, four of which are independent.

In this discussion the piezoelectric constants have been considered with respect to the crystallographic axes. When a crystal plate is cut at an oblique angle, the electric field is in general no longer parallel to one of the crystallographic axes; and a new set of piezoelectric constants has to be computed, by using the customary formulas for transformation to an axial system corresponding to the particular cut in question.

11. The piezoelectric constants. From the foregoing equations it is evident that δ has the dimensions of the reciprocal of an electric field strength, or, on the electrostatic system of units $[M^{-\frac{1}{2}}L^{\frac{1}{2}}Tk^{\frac{1}{2}}]$, while the dimensions of ϵ are those of a polarization $[M^{\frac{1}{2}}L^{-\frac{1}{2}}T^{-1}k^{\frac{1}{2}}]$. It is im-

portant to note that the only dimension of the product $\delta\epsilon$ is [k]. Using the practical system of units, we may express δ in terms of coulombs per kilogram weight and ϵ in coulombs per square centimeter. It is customary, however, to use the electrostatic c.g.s. system.

For example, the following values[8] of δ and ϵ for quartz and Rochelle salt are expressed in statcoulombs per dyne and statcoulombs per square centimeter, respectively.

Right quartz (for left quartz the signs are reversed): $\delta_{11}=-\delta_{12}=-\delta_{26}/2=6.9\times10^{-8}$; $\delta_{14}=-\delta_{25}=-1.7\times10^{-8}$; $\epsilon_{11}=-\epsilon_{12}=-\epsilon_{26}=5.1\times10^{4}$; $\epsilon_{14}=-\epsilon_{25}=1.35\times10^{4}$. Under all ordinary circumstances these values are practically independent of temperature.

Rochelle salt: $\delta_{14}=340$ to 1180×10^{-8}; $\delta_{25}=-165\times10^{-8}$; $\delta_{36}=35\times10^{-8}$; $\epsilon_{14}=56$ to 194×10^{4}; $\epsilon_{25}=-5.33\times10^{4}$; $\epsilon_{36}=4.34\times10^{4}$. Recent investigations indicate that the I.C.T. value of δ_{11} for quartz is somewhat too high, a more representative value being -6.5×10^{-8}; while for Rochelle salt enormously high values of δ_{14} have been recorded, as indicated below.

12. Secondary effects. When mechanical stress is applied to a piezoelectric crystal, the resulting polarization, through the action of surface or body charges, gives rise in general to an electric field, which in turn produces a secondary stress. The latter always *opposes* the impressed stress and diminishes the strain. For example, in the measurement of elastic constants, it is clear that unless special precautions are taken, the observed compliance coefficients will be too small. Such "depolarizing fields" are frequently present in vibrating crystal resonators.

The following simple example will show how this comes about. Let a single static stress X_x be impressed on an isolated X-cut quartz plate without electrodes. In view of Eqs. (8), the piezoelectric component of polarization is $P_x=-\delta_{11}X_x$. The polarization charges on the surfaces cause in the plate a *counter* field $E_x'=4\pi\delta_{11}X_x/k$, which in turn, by Eqs. (11), causes a counter strain $x_x'=\delta_{11}E_x'$ as well as a counter polarization $P_x'=\eta E_x'$, where η is the dielectric susceptibility. We have then for the total strain, from Eq. (3), $x_x=-(s_{11}-4\pi\delta_{11}^2/k)X_x$. The elastic compliance s_{11} is thus, through piezoelectric reaction, diminished by the amount $4\pi\delta_{11}^2/k$, which for quartz is about 1 percent of s_{11}.

The polarization also suffers a diminution through the depolarizing action of the counter field. The resulting value is $P_x+P_x'=-\delta_{11}X_x\times(1-4\pi\eta/k)=-\delta_{11}X_x/k$. The effective value of the constant δ_{11} is thus reduced to only $1/k$ of its normal value; by this we mean the value which, when multiplied by X_x, would give the total polarization if the field were zero. The depolarizing effect can be extremely large in Rochelle salt. It is strictly analogous to the magnetic depolarization that takes place in the interior of a short, thick bar magnet or in a magnetic shell. To a greater or less degree it has to be taken into account in the theory of the piezoelectric resonator.

13. A very important consequence of the secondary effects is the *variation of the effective dielectric constant with strain.* Let the field in the crystal, from some external source, be E_h, where h represents x, y, or z. Then, if the crystal is so clamped that all strains are suppressed, the polarization in the h-direction is the same as if the crystal were not piezoelectric; that is,

$$P_h''=\eta_{hh}''E_h. \tag{12}$$

The double primes indicate the clamped state. If now the clamps are removed, six strain components $x_x=\delta_{h1}E_h$, $\cdots$ $x_y=\delta_{h6}E_h$ appear (in the most general case) through the converse effect. Owing to the direct effect, each of these strains causes a component of polarization, so that the total *piezoelectric* polarization is $P_h'=\epsilon_{h1}x_x+\cdots+\epsilon_{h6}x_y$. On combining this with Eq. (12) we have, as the complete expression for the polarization,

$$P_h=P_h''+P_h'=(\eta_{hh}''+\sum_{i=1}^{6}\epsilon_{hi}\delta_{hi})\equiv\eta_{hh}'E_h,$$

where η_{hh}' is the susceptibility of the *unclamped* crystal. For the dielectric constant we have, in the clamped state, $k_{hh}''=1+4\pi\eta_{hh}''$, and for the mechanically free crystal,

$$k_{hh}'=k_{hh}''+4\pi\sum_{i=1}^{6}\epsilon_{hi}\delta_{hi}. \tag{13}$$

This means that, if a piezoelectric crystal is unconstrained, its dielectric constant is increased by an amount which is a function of certain of its piezoelectric constants; this contribution is always positive. In most crystals the piezoelectric part of Eq. (13) is very small. For quartz, in a direction parallel to the x-axis it is about 2

[8] These data and those for many other substances are given in reference 4.

percent of the first term; in Rochelle salt it may be hundreds of times larger than the first term—which of itself is very large—and indeed in Rochelle salt the dielectric constant theoretically approaches infinity under certain conditions!

Cases frequently arise, especially with vibrating crystals, in which *partial* constraints are present, giving values of the dielectric constant intermediate between k'' and k'.

All published values of the dielectric constant k of piezoelectric crystals, as well as the occurrence of the unprimed symbol k itself, may in general be assumed to apply to crystals in the *unconstrained* state, with due regard to the direction of the electric field. Thus in general k signifies the quantity given in Eq. (13).

Rochelle salt

14. This substance is so important on both theoretical and technical grounds that it will be considered somewhat at length. Rochelle salt (*"sel de Seignette"*) is a double tartrate of potassium and sodium ($NaKC_4H_4O_6 \cdot 4H_2O$), commonly regarded as belonging to the orthorhombic sphenoidal class. Like quartz, Rochelle salt is enantiomorphic, but it is always of the right-handed form. Together with certain isomorphic relatives, in which the K is partially replaced by admixtures of NH_4, Rb, or Tl, it constitutes a family of crystals with properties so unique that they are sometimes given a special name, the "Seignette-electrics."[9]

We shall consider only Rochelle salt itself. Its outstanding feature, which pointed the way to the discovery of other remarkable properties, is the huge piezoelectric effect, unapproached by any other known substance. In spite of rather poor mechanical strength and low temperature of disintegration (55°C), Rochelle salt finds important applications, especially in the field of acoustics. Of chief scientific interest are its electric anomalies. The present survey can hardly give more than a hint of the main experimental and theoretical results found in the voluminous literature on this remarkable crystal.[9, 10]

The anomalies in Rochelle salt are confined to effects observed with fields in the x-direction and shearing stresses in the yz-plane. The piezoelectric constants δ_{25} and δ_{36} (Sec. 11), though larger than for most other crystals, exhibit no special peculiarities, nor do the dielectric constants for the y- and z-directions, both values being in the neighborhood of 10 and having small temperature coefficients.

For electric fields in the x-direction the dielectric properties of Rochelle salt exhibit the much discussed *ferromagnetic analogy*. Just as iron and other ferromagnetics are characterized by a maximum in permeability at a certain temperature—the Curie point, above which the permeability decreases rapidly—so in Rochelle salt there is also a transition-temperature, called by analogy the "Curie point," at which a similar change takes place in the dielectric constant k_x. In iron the Curie point is around 770°C, while for Rochelle salt it is 23.7°C, only slightly above room temperature. In contrast to iron, however, the large values of k_x are confined to a limited range of temperature, from 23.7° to −18°C (these are Mueller's values; Kurtschatov finds 22.5° and −15°). The lower critical temperature has been termed the "lower Curie point." Below it, the dielectric properties are similar to those above the upper Curie point; the region, however, has been comparatively little investigated. For brevity, the upper and lower Curie points will be designated by Θ and Θ_1, respectively.

15. Theory of Rochelle salt. The behavior of Rochelle salt can best be understood in the light of the present theory, which has been evolved from Debye's dipole theory, in a manner parallel to Weiss' development of ferromagnetic theory from Langevin's work on diamagnetics. The first important steps were taken by Kurtschatov. They were further extended by Mueller, who made use not only of dielectric data but of optical, pyroelectric, and piezoelectric as well. Among the earlier theoretical treatments may be mentioned those of Fowler[11] and David.[12]

The best evidence at present indicates that a Rochelle salt crystal, like iron, is made up of distinct "domains," each of which possesses, between the Curie points, a definite spontaneous electric polarization having a flat maximum of about 600 e.s.u. at 0°C, diminishing to zero at Θ

[9] I. V. Kurtschatov, *Seignette Electricity* (Moscow, 1933), in Russian; French translation entitled *Le champ moléculaire dans les diélectriques* (Paris, 1936).

[10] H. Mueller, Phys. Rev. **47**, 175–191 (1935).

[11] R. H. Fowler, Proc. Roy. Soc. **A149**, 1–28 (1935).

[12] R. David, Helv. Phys. Acta **8**, 431–484 (1935).

and Θ_1 (Fig. 6). Some of the domains are polarized in one direction, some in the other, along the x-axis. Each domain is so large—of the order of a centimeter—that many, if not all, crystals exhibit *unipolarity*, which is observable as a lack of symmetry in the polarization curve for positive and negative fields. In this respect Rochelle salt differs from iron, as well as in the fact that the direction of the spontaneous polarization is always parallel to the x-axis.

The polarization in each domain is believed to be due to electric dipoles, which can rotate in the crystal lattice; they are probably the water molecules. At any given temperature between the Curie points, a certain small fraction of all the dipoles are oriented in the x-direction, thus constituting the spontaneous polarization. The remaining dipoles give to the crystal the properties of an ordinary dielectric of large dielectric constant k_x.

The spontaneous polarization between the Curie points must, according to Sec. 4, make the crystal pyroelectric; in this range Rochelle salt should therefore be assigned to the monoclinic hemimorphic crystal class.[13] As the temperature increases through the upper Curie point, the dipoles fall into a state of disorder, which destroys the spontaneous polarization and makes the pyroelectric effect vanish. The symmetry of the crystal is thereby raised to that of the orthorhombic sphenoidal class, to which Rochelle salt is commonly assigned. Below the lower Curie point a higher degree of order is attained, in which the dipoles become systematically so oriented that there is no resultant spontaneous polarization, and the symmetry of the crystal is the same as that above the upper Curie point.

The Curie points, then, are crystallographic *inversion points*, analogous, for example, to the transition from α- to β-quartz at 573°C. In contrast to quartz, however, the transition here is from a nonpyroelectric to a pyroelectric class, in which case Jaffe has shown quite generally, from considerations of crystallographic symmetry, that one should expect the dielectric constant to approach an infinite value at the transition points. As either transition temperature is approached, the energy necessary to accomplish the reversal of domains (corresponding to the low values of polarization at very small fields) diminishes, approaching zero at the transition points. The fundamentally characteristic feature of Rochelle salt is not so much the large change in polarization with small change in field (large k_a), as the possession, over a certain temperature range, of a *reversible spontaneous polarization*. This is what distinguishes the "Seignette-electrics" from other dielectrics, the effect being most pronounced with pure Rochelle salt.

[13] H. von R. Jaffe, Phys. Rev. **51**, 43–47 (1937).

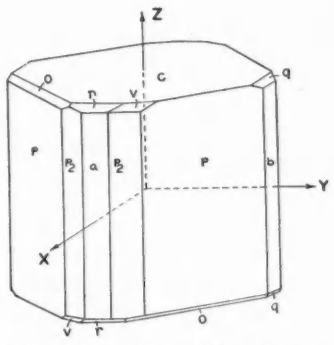


FIG. 3. A typical Rochelle salt crystal. The c-faces (top and base of the prism) and the prismatic p-faces are generally the most developed. The other faces are often very small or absent.

It is proverbial that no analogy should be pushed too far. In the case of the ferromagnetic analogy of the dielectric properties of Rochelle salt, it is clear that the causes are different, and that nothing like Heisenberg's forces of interaction have to be postulated as in ferromagnetics. Above the upper Curie point the laws are identical; between the Curie points they are analogous; within this range Rochelle salt is comparable to iron *near its Curie temperature*. There is also a certain analogy between the strain-sensitivity and magnetostriction in ferromagnetic materials, and the piezoelectric properties of Rochelle salt.

Finally, it may be said that while in most unmagnetized ferromagnetic substances the domains, unlike those in Rochelle salt, have a choice of 3 axes, still there is one ferromagnetic crystal, pyrrhotite (Fe_7S_8, hexagonal), some specimens of which have a spontaneous magnetic moment confined to one direction.[14]

16. Results of experiments with Rochelle salt. We now consider a few of the many investigations that have contributed to the present theory of Rochelle salt, and which include measurements of polarization under varying electric fields or mechanical stresses, or both, made at different temperatures and with frequencies ranging from zero to 7.5×10^8 cycle/sec. There is great discordance in numerical values among published papers.

Rochelle salt crystals (Fig. 3) are commonly grown from "seeds" in a hot saturated solution

[14] F. Bitter, *Introduction to Ferromagnetism* (1937), p. 209.

which is allowed to cool slowly. Perfectly clear crystals weighing several pounds have been made in the Brush Laboratories.

In the piezoelectric observations it is customary to impress the stress by compression in the yz-plane in a direction 45° from the y- and z-axes. To this end an X-cut plate or bar is prepared with its edges in the 45° directions. Plates thus oriented are also widely used in applications of the converse effect, when it is desired to make use of the *elongation* of a Rochelle salt plate under an impressed field. We have here an instance of the change in piezoelectric constant with transformed axes mentioned in Sec. 8; for, when the x-, y-, z-axes are transformed to x'-, y'-, z'-axes by a rotation of 45° in the yz-plane, the piezoelectric effect (for field parallel to x) with respect to the new axes is expressed by two constants, $\delta_{12}' = \delta_{14}/2$ and $\delta_{13}' = -\delta_{14}/2$. Each of these constants represents a transverse effect (Fig. 4), indicating, for a field in the positive x-direction, an elongation parallel to y' and a contraction parallel to z'. Similarly, when a compressional stress Y_y' (or Z_z') is applied to such a plate along the y'- (or z'-) axis, the polarization due to the direct piezoelectric effect is given by $-P_x = \delta_{12}' Y_y'$ (or $\delta_{13}' Z_z'$), whence δ_{14} can be computed.

17. Dielectric properties of Rochelle salt between the Curie points. The outstanding features are: the similarity of the polarization curve (polarization *vs.* electric field) to the curve of magnetization for iron, showing small polarization at fields below a value lying between 15 and 50 volt/cm, then a rapid increase followed by saturation from about 200 volt/cm on; with alternating fields, hysteresis loops are formed except in weak fields (below 50 volt/cm); mechanical constraints distort the hysteresis loops and reduce the polarization. After prolonged charge or severe mechanical stress the crystal becomes fatigued, causing its behavior to be considerably affected by past history. This effect was shown by Kurtschatov to be due to surface layers.

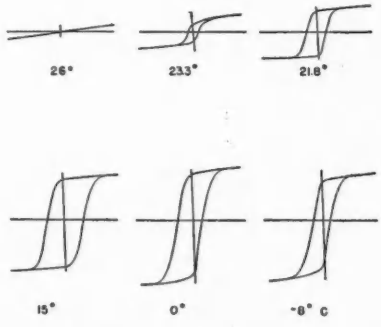


FIG. 4. Rochelle salt hysteresis curves, 60~a.c. The abscissas are in volts per centimeter, max. 387; the ordinates are proportional to the polarization.

As an example of the hysteresis loops, from which interesting conclusions may be drawn, some of the observations by Sawyer and Tower[15] are reproduced in Fig. 4. The similarity to magnetization curves is inescapable. One notes also the maximum in polarization at 0°C and the low polarization and disappearance of hysteresis at 26°; that is, above the upper Curie point. At 15°, exclusive of the range of saturation, the over-all value of k_x is about 10,500; the maximum instantaneous value is at least 200,000; along the saturation range the value drops to about 300, of the same order of magnitude as that discussed later for a completely constrained crystal. The rapid rise of the polarization curve (reversal of domains) does not take place, when alternating current is used, until the field reaches a value of 50 to 100 volt/cm. On the other hand, a static field of 15 volt/cm or less suffices to reverse the domains when sufficient time, amounting in some cases to several seconds, is allowed to elapse. The

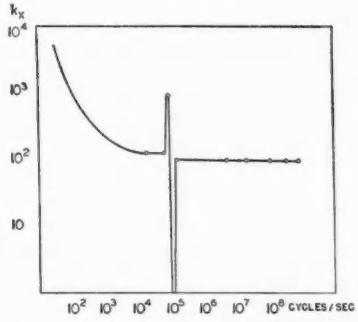


FIG. 5. Dependence of dielectric constant of Rochelle salt upon frequency. Near 10^5 cycle/sec the crystal used in this experiment was in resonant vibration.

[15] C. B. Sawyer and C. H. Tower, Phys. Rev. **35**, 269–273 (1930).

results of other workers are in general agreement with these, at least in order of magnitude.

In the high frequency range several observers have recorded values of k_x at various fields, frequencies, and temperatures. It must suffice here to say that with small fields k_x is around 300 at all frequencies down to zero, except in the immediate neighborhood of the Curie points; with large fields k_x diminishes from the order of 1000 at 10 kc/sec down to values in the neighborhood of 100 at the highest frequencies. As is to be expected, abnormal values occur at those frequencies at which the crystal vibrates in resonance. Fairly representative values of k_x at different frequencies are shown in Fig. 5, taken from a recent paper by Bantle and Busch.[16] The sharp maximum and minimum in the curve at a frequency slightly above 100 kc/sec are due to the fact that here the frequency passed through the resonance range of vibration of the crystal (*cf.* Fig. 7).

Of great importance in connection with the theory discussed in Sec. 15 is the fact that at all frequencies the dielectric constant rises to very high maximums at the Curie points.

18. Piezoelectric properties of Rochelle salt between the Curie points. From Eq. (13) it is to be expected that k_x will show a marked dependence on δ_{14}, especially in view of the exceptionally large value of the latter quantity. This is indeed the case, and the only reason for having considered the dielectric constant first is that in the literature so much more attention has been paid to the dielectric properties.

In general, the piezoelectric are found to run parallel to the dielectric properties. This statement includes the form of the polarization-stress curve, the presence of time-lag and fatigue, and large values of δ_{14} between the Curie points, rising to maximums at these points. A saturation value for the piezoelectric polarization has been found at pressures of about 30 kg/cm^2. Values of δ_{14} as high as $30{,}000\times10^{-8}$ have been recorded close to the upper Curie point.[17, 18]

The close relationship between k_x and δ_{14} expressed by Eq. (13) is well exemplified by the

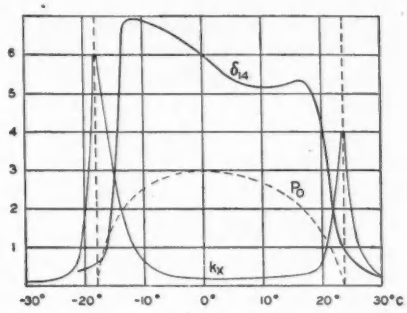


FIG. 6. Variation of dielectric constant k_x, piezoelectric constant δ_{14}, and spontaneous polarization P_0 of Rochelle salt with temperature. For k_x, 1 div. = 1000 units; for δ_{14}, 600×10^{-8}; for P_0, 200 e.s.u. The numerical values are only rough approximations; wide discrepancies are found in the literature.

experiments previously referred to, in which hysteresis loops were recorded while the crystal was under mechanical constraint.[10, 12, 15] In extreme cases the piezoelectric effect was so suppressed that the "loops" became straight lines of small slope, indicating a small and constant value of k_x.

The value of k_x for a completely constrained Rochelle salt crystal is probably about 100. This is the value obtained at very high frequency when strains in the crystal are inhibited by inertia. Although no complete and reliable observations of both k_x and δ_{14} seem ever to have been recorded for the same crystal, there is no reason to suppose that the relation between these two quantities is not correctly expressed by Eq. (13).

19. Rochelle salt outside of the Curie points. Here Rochelle salt is analogous to iron in its paramagnetic state above the Curie point. Fatigue, lag, saturation, and hysteresis are absent. Both k_x and δ_{14} decrease, at first rapidly and then more slowly, from the large values at the Curie points.

With unconstrained crystals, a law identical with the Curie-Weiss law for the paramagnetic state of iron has been found to hold above the upper Curie point.[10, 19] From Mueller's observations one finds k_x equal to 70 at 50°C. Below the lower Curie point, k_x decreases to about 7 at $-160°$. For δ_{14}, values from 100×10^{-8} to 400×10^{-8} have been found at temperatures well outside of the range from Θ to Θ_1.

[16] W. Bantle and G. Busch, Helv. Phys. Acta **10**, 262–264 (1937).
[17] R. D. Schulwas-Sorokin, Zeits. f. Physik **73**, 700–706 (1932).
[18] W. G. Cady, Proc. Phys. Soc. **49**, 646–653 (1937).
[19] O. Norgorden, Phys. Rev. **49**, 820–828 (1936); **50**, 782 (1936).

Some representative values of k_x, δ_{14}, and the spontaneous polarization P_0 (Sec. 15) have been assembled in Fig. 6 to show the dependence upon temperature.

20. The converse effect in Rochelle salt. The amount of shear, or the elongation of a 45° bar, caused by an electric field has received investigation.[15, 19–21] The means employed include the microscope, mechanical dilatometer, and change in capacitance of a small condenser. Under varying stresses and temperatures the effects run, in general, parallel to those observed with the direct effect. There are some discrepancies, and there is evidence that δ_{14} has a greater value under similar conditions than in the direct effect. This fact, as well as the existence of hysteresis, points to lack of that perfect reversibility in the phenomena which was postulated in Sec. 2.

The Piezoelectric resonator

21. The most important application of piezoelectricity is in the frequency-control of radio circuits. Quartz is employed almost exclusively, though certain advantages have been claimed for tourmaline at the highest frequencies. Quartz is relatively cheap and abundant, extremely durable, and of very low internal viscosity. Rochelle salt resonators respond vigorously, but are very inferior mechanically and thermally.

A piezo-resonator is a condenser with vibrating dielectric. According to the type of crystal and cut, the vibrations may be of any mode—compressional, shear, flexural, torsional, or combinations of them. When an alternating field of any frequency is applied, alternating mechanical stresses are created through the converse effect (Eqs. 10). They set the crystal into a state of forced vibration, with an amplitude that is negligible except near the frequency of some natural mode of vibration. Here, thanks to the extremely low mechanical decrement, the amplitude of vibration is multiplied thousands of times. The direct piezoelectric effect then comes into play through Eqs. (8), resulting in a polarization which in turn causes charges on the electrodes and reactions upon the driving circuit. When vibrating, the crystal absorbs energy and behaves like a condenser and resistor in parallel, both capacitance and resistance varying with frequency. It is only too easy for the amplitude at resonance to become so great as to fracture the crystal.

[20] S. Bloomenthal, Physics **4**, 172–177 (1933).
[21] C. I. Vigness, Phys. Rev. **46**, 255–257 (1934).

For radiofrequencies above a few hundred kilocycles, use is made chiefly of the *thickness vibrations* of quartz plates, in which there is a system of plane stationary waves having their direction of propagation in the thickness direction normal to the flat surfaces. The mode of vibration may be compressional (the X-cut, with longitudinal vibrations, using one of the "L" effects in Fig. 2) or shear (the Y-cut, with transverse vibrations). In the latter case the particles vibrate in a direction parallel to the plane of the plate, and the piezoelectric excitation is of the type T' in Fig. 2. At the fundamental frequency the thickness dimension is half a wave-length and there is a nodal plane midway between the two faces.

Letting l denote the thickness in centimeters, ρ the density (2.654 gm/cm³ for quartz), E the elastic modulus, v the speed of wave propagation in the crystal, we have for the frequency,

$$f = v/2l = (1/2l)E^{\frac{1}{2}}/\rho^{\frac{1}{2}}. \qquad (14)$$

For quartz, X-cut, $E = c_{11}$; for the Y-cut, $E = c_{66}$. The values from static measurements are $c_{11} = 8.54 \times 10^{11}$, $c_{66} = 3.91 \times 10^{11}$ dyne/cm². When calculated from vibrating plates, slight differences are usually found. With quartz it is not customary to cut plates thinner than for 5×10^6 cycle/sec (thickness about 0.6 mm), though much thinner plates can be made to operate. Frequencies as high as 100×10^6 cycle/sec have been reported for tourmaline. The frequency of an X-cut plate increases slightly with temperature, while that of a Y-cut plate decreases. In recent years various oblique cuts have been introduced, in which the mode of vibration is similar to that of the Y-cut, but with a frequency that is practically independent of temperature over a considerable range. For many purposes this renders unnecessary the thermostats in which crystals of the earlier cuts are commonly placed.

Unfortunately, thickness vibrations are troubled with a serious pest, in the form of parasitic vibrations. These are usually overtones of various low frequency modes—compressional, flexural, or torsional. They give rise to complicated wave systems, with the result that a large number of resonant frequencies close together are observed, instead of the single frequency in Eq. (14). By various means their effect can be largely mitigated. Wave-patterns in crystals of various forms have been studied by optical methods and by x-rays.

22. For resonators of lower frequencies, the ideal form is that of a *bar* of small cross section, *vibrating longitudinally*, since then the absence of

parasitic frequencies insures a single well-marked frequency of response. Owing to the small electrode area, this ideal form is suitable only with very small amounts of energy. Otherwise, rectangular plates are used, necessitating special formulas to take account of the more complicated mode of vibration. In this case the vibrations may be either longitudinal (in the direction of length or breadth) or of a shear type, in which the plate becomes distorted back and forth by shearing strains in its own plane. All of these modes can be realized with quartz. A typical and much used example is an X-cut bar or elongated plate vibrating lengthwise, with its length in the y-direction. The transverse effect is utilized, whereby, according to Eqs. (10), $-Y_y=\epsilon_{12}E_x$. Eq. (14) gives the frequency, letting l represent the length and taking $E=7.7\times10^{11}$ dyne/cm^2.

For various experimental or technical purposes, still other shapes of resonators are used—bars of oblique orientation, circular plates, cylinders, tubes, spheres, and especially the quartz rings that serve as master oscillators in some of the crystal clocks.

Whatever the form of the crystal, there are usually several fundamental frequencies, together with numerous overtones, all capable of excitation. Our satisfaction over the fact that a single crystal can be used as a standard for many different frequencies is sometimes alloyed by overabundance of riches in this respect.

23. A very important step in the adaptation of piezo-resonators to electric circuits was taken by Van Dyke[22] and Dye,[23] who showed independently that the crystal with its electrodes can be represented by certain *equivalent electrical constants*. The procedure of replacing the mechanical constants of an electromechanical device by electrical quantities is well known in the case of such acoustic devices as loudspeakers, phonograph pick-ups, etc. In the present case the resonator has a motional impedance equivalent to that of a circuit of two branches in parallel, one branch containing simply the capacitance C_1 of the resonator when not vibrating, the other branch consisting of an equivalent inductance L, resistance R, and capacitance C in series. In the neighborhood of any one resonance frequency, R, L, and C are constant, but they assume different values at other resonance frequencies for the same crystal. These quantities can be measured electrically; and, at least for the simpler modes of vibration, they can also be calculated theoretically from the dimensions, density, elasticity, and the dielectric and piezoelectric constants. It is thus possible to predetermine the shape and size of a resonator for any desired electric characteristics.

The advantage in representing the piezoelectric resonator in terms of its equivalent electric constants L, R, C, and C_1 lies in the fact that these *are* constants for a given mode of vibration, whereas the representation in terms of a capacitance and resistance in parallel (or in series) mentioned in Sec. 21 is open to the objection that the values of these quantities vary enormously within the range of resonance.

Consideration of the magnitude of the equivalent constants shows at once why a quartz resonator is so superior to the combination of coil and condenser for the control or measurement of frequency. For example, one of Dye's X-cut bars measuring about $60\times6\times1.5$ mm had a frequency of lengthwise vibration of 44.095 kc/sec. Dye found L to be 160 h; R, 1500 ohm; C, 0.08$\mu\mu$f; C_1, 8$\mu\mu$f. The logarithmic decrement, $R/2fL$, was only 0.0001. The outstanding advantages offered by quartz are its low energy losses and its great mechanical stiffness, to which the series capacitance C is inversely proportional. Indeed, in resonators as commonly mounted, including the example just cited, frictional losses from contact with the electrodes and surrounding air account for most of the observed resistance R. With a quartz bar having suitably etched and polished surfaces, with silver electrodes plated directly on the crystal, and suspended in vacuum, a logarithmic decrement

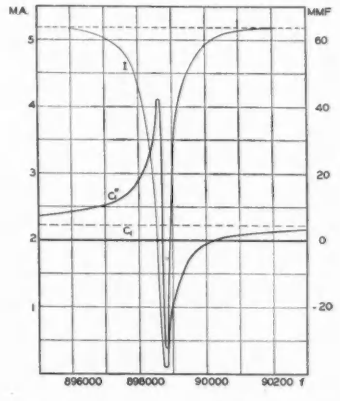


FIG. 7. Resonance curves for a quartz bar.

[22] K. S. Van Dyke, Phys. Rev. **25**, 895 (1925).
[23] D. W. Dye, Proc. Phys. Soc. **38**, 399–457 (1926).

per cycle of only 5.4×10^{-6} has been recorded.[24] Very recently in this laboratory Van Dyke has obtained, with a quartz ring in vacuum, a decrement of the extremely low value of 9×10^{-7}.

24. In Fig. 7 are seen resonance curves obtained in 1922 by impressing a variable frequency upon a coil and variable condenser in series, the crystal (X-cut quartz bar $30\times4\times1.4$ mm, frequency 89,870, in simple mounting without modern refinements) being in parallel with the condenser. At each frequency the condenser was so tuned as to make the current I in the coil a maximum. The dotted portion shows the value that I would have if the crystal were so constrained as not to vibrate. With the crystal free, the current sank to a sharp minimum. C_1 is the constant capacitance of the nonvibrating crystal, while C_1'' is the equivalent parallel capacitance of the vibrating crystal referred to in Sec 21. As resonance is approached, C_1'' rises above the value C_1 which it had before the crystal began to vibrate perceptibly, reaches a maximum just below the resonance frequency, then falls very rapidly to *negative* values, with a minimum just above resonance. The negative values on the high frequency side of resonance mean that here the crystal has an *inductive* reactance, a fact that is easily explained when the equivalent circuit $LRCC_1$ is considered.[25]

The logarithmic decrement of the crystal shown in Fig. 7 is 6.6×10^{-4}. While the resonance appears fairly sharp, it is in fact nearly a thousand times broader than that attainable by the methods described in the preceding section.

25. The piezo-oscillator. We have hitherto considered the piezo-resonator as driven by an independent source of alternating current. In the earliest investigations it was found that the crystal exerted a stabilizing effect upon the generating circuit. This was soon followed by the discovery that the crystal could be so connected to a triode generator as to assume practically complete control of the frequency, in a manner closely analogous to that in which a pendulum or balance-wheel controls the frequency of a clock.[26] Since then many modifications and improvements have been introduced; but the arrangement that is basic for nearly all piezo-oscillators is the "Pierce circuit"[27] (Fig. 8). The crystal is usually in the grid circuit as shown, although for the lower range of frequencies it is sometimes connected between grid and plate. In Fig. 8, coupling between grid and plate circuits is supplied by the capacitance of the tube. The tank circuit has very little effect on the frequency, serving mainly to adjust the phase relations. When the crystal vibrates, the alternating charges induced piezoelectrically on its electrodes control the grid potential and thus the output current; and, with proper setting of the condenser, the phase relations are such as to make the oscillations self-sustaining at a frequency slightly *above* the natural frequency of the crystal. The output power can be amplified many thousands of times, the frequency remaining strictly controlled by the quartz "master oscillator."

26. Special types of piezo-resonator and oscillator. (*a*) *Luminous resonators.* Slender quartz rods, of the type described in Sec. 22, have been mounted in helium or argon at low pressure. When the frequency from a source of low power coincides with the natural frequency of the fundamental or of any one of numerous overtones, the rods vibrate with amplitude sufficient to cause the piezoelectric charges in the regions of maximum strain to ionize the gas. By counting the number of glowing regions the order of harmonic can be determined. These resonators serve as frequency standards of considerable precision and have come into some use, especially in Germany.

(*b*) *Resonators in the acoustic range.* Tuning forks have been successfully driven by small Rochelle salt plates cemented to their arms.

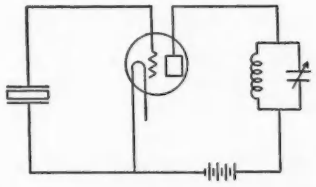


FIG. 8. Simplified piezo-oscillator circuit.

[24] K. S. Van Dyke, Proc. I. R. E. **23**, 386–392 (1935).
[25] W. G. Cady, Proc. Am. Acad. Arts & Sci. **68**, 383–409 (1933); Physics **7**, 237–259 (1936).
[26] W. G. Cady, Proc. I. R. E. **10**, 83–114 (1922).
[27] G. W. Pierce, Proc. Am. Acad. Arts & Sci. **59**, 81–106 (1923). See also American Radio Relay League, *Radio Amateur's Handbook* (ed. 15, West Hartford, Conn., 1937).

The same is true of long straight metal rods or tubes, to the centers of which two or more quartz or Rochelle salt plates are attached and connected to the output and input of an amplifier, so that the rod is kept in sustained vibration at its natural longitudinal frequency. At the Paris Exposition in 1937, Duc de Gramont had an interesting exhibit of acoustic quartz resonators of a type first described for use in static fields by the Curies. Each resonator consisted of two very thin X-cut strips cemented together with polarities opposed, so that in an electric field one tended to elongate, the other to contract, the device thus flexing like a bimetallic thermostat. This action caused flexural vibrations of relatively low frequency to be set up, producing audible notes of various pitches.

(*c*) *The quartz clock.* First introduced in 1929, this device has found a wide and important field of usefulness and is now considered superior in constancy to the best pendulum clocks. It consists essentially of a quartz oscillator of low temperature coefficient, which, together with accessory apparatus, is kept at constant temperature. By frequency-demultiplying circuits the fundamental frequency, usually of the order of 10^5 cycle/sec, is brought down to 10^3 cycle/sec; and the output at this low frequency drives a synchronous motor geared to the hands of the clock. In some cases the frequency has remained constant to within 2 parts in 10^8 over a period of six months of constant operation.

(*d*) *Crystal filters.* The sharply selective property of quartz resonators (Fig. 7) made it evident in the earliest investigations in this field that one important application might be as an electric filter. Quartz plates of special design are now in regular use as filters for carrier-current telegraphy and telephony. By associating quartz plates with suitable coils and condensers, high, low, or pass-band filters of any radiofrequency can be made, with very sharp cut-off. Filters of quartz, or of metal rods with small Rochelle salt plates attached, are also used to some extent in superheterodyne reception.

Ultrasonics

27. The starting point for this part of the subject was the work of Langevin and Chilowsky in France, who in 1917 developed a piezoelectric transmitter-receiver for use under water in the detection of submarines by the echo method. This "quartz sandwich" consisted of two massive slabs of metal, between which was cemented a large X-cut quartz plate, or a mosaic of smaller plates. The slabs served as electrodes, and from one of them compressional waves were transmitted in the form of a fairly narrow beam to the surrounding water, with a frequency around 4×10^4 cycle/sec. The returning echo set the "sandwich" in vibration with an amplitude sufficient for detection by means of amplifiers. A similar device has been found useful for depth-sounding.

Since then there have been many investigations in ultrasonics, using both progressive and stationary waves in solids, liquids, or gases.[28] In some cases the source is the magnetostriction oscillator invented by G. W. Pierce, who also first experimented with ultrasonic waves in air from a quartz crystal. The quartz oscillator is usually an X-cut plate with thin metal electrodes, vibrating in the thickness direction, and driven by a tube generator; for example, a Hartley oscillator. Tourmaline has also been used, as well as an obliquely cut plate of Rochelle salt.[18]

The shortest ultrasonic waves are produced by driving a quartz crystal at the frequency of one of its higher overtones. By this means frequencies up to about 5×10^8 cycle/sec can be employed, corresponding to a length of the sound wave in air of 6×10^{-5} cm, of the order of the wavelength of visible light. Power in the form of ultrasonic radiation as high as 10 watt/cm^2 has been produced; this is 10^9 times (80 decibels) greater than the average power per square centimeter radiated in sound waves from a loudspeaker.

When a 300-kc/sec quartz oscillator produces 10 watt/cm^2 in water, the amplitude of pressure in the water is ±5 atmospheres, the maximum acceleration approximately 10^5 *g*. The water particles move with maximum speed of 40 cm/sec, and the radiation pressure is about 1300 dyne/cm^2 or 0.0013 atmosphere. The authority for this statement is Bergmann (Ref.

[28] L. Bergmann, *Der Ultraschall und seine Anwendung in Wissenschaft und Technik.* (VDI-Verlag, Berlin, 1937); E. Hiedemann, *Ultraschall. Ergebnisse der exakten Naturwissenschaften* (Springer, Berlin, 1935), vol. 14, pp. 201–263.

28, p. 39). One would expect that under these conditions the phenomenon of cavitation would modify the results, especially if air were present in the water.

The effects of intense ultrasonic waves can be demonstrated in various mechanical and thermal ways, some of which are quite sensational.[28, 29] In recent years much attention has been given to their effect upon a beam of light. In 1932 it was discovered by Debye and Sears (also independently by Lucas and Biquard) that the closely spaced planes of condensation and rarefaction in a liquid that is being traversed by ultrasonic waves, cause the medium to act like an optical grating. A beam of light in a direction normal to the direction of propagation of the sound becomes *diffracted*, so that spectra of several orders can sometimes be seen. The full theory is quite complicated.

This diffraction method has undergone many modifications and has been used, among other things, for the measurement of elastic constants of both liquid and solid substances. It has also found an application in television, for modulating the beam of light used in viewing the image. This is done by applying the modulated voltage to the electrodes of the crystal that emits the ultrasonic waves.

Ultrasonic waves have been found useful in investigating the state of vibration in various parts of the quartz oscillator itself and in measuring speed and absorption of sound in gases. Intense ultrasonic beams have very marked chemical and biological effects upon many substances exposed to them; they have a coagulating effect upon dust and smoke; particles of colloidal material suspended in a liquid are torn to pieces, resulting in extremely fine emulsions. Some of these effects are already being used in industry.

Miscellaneous applications of piezoelectric crystals

28. Rochelle salt is now widely used in the construction of microphones, loudspeakers, telephone headsets, and phonograph pickups. The amount of strain for a given applied voltage is increased by the use of "bimorph elements," consisting of two thin plates cemented together, after the manner mentioned in Sec. 26 (*b*). Rochelle salt has also been used as an ink-recorder, and, in physiological investigations, for measuring muscular movements. Both Rochelle salt and quartz have been employed as moving elements in oscillographs.

In applications involving large stresses, quartz is used chiefly. Examples are the measurement of vibrations in machinery, of pressures exerted by explosives, and of the cutting force of tools. Piezoelectric crystals have also found their way into engine indicators, acceleration meters, and instruments for recording earth tremors.

Some demonstrations in piezoelectricity

(*a*) The direct effect can be demonstrated with an X-cut rectangular plate of Rochelle salt measuring, say, $6\times3\times0.5$ cm, with its long edges at 45° with the y- and z-axes. The large faces are coated with tinfoil, from which wires lead to a small neon lamp. When the plate is suddenly compressed endwise by a sharp blow, the lamp flashes. To avoid fracturing the crystal, it is best to protect the ends with armatures of soft wood. The protection must not be too soft, for then the compression will not be sufficiently rapid.

(*b*) For the converse effect, the same Rochelle salt plate can be connected directly to the 115-v a.c. lighting circuit, or, still better, to a 230-v source. A faint hum will be heard, which can be increased by pressing sheets of solid material against the ends, to serve as sounding boards.

(*c*) Almost any fragment of piezoelectric crystal will cause one or more audible "clicks" in a telephone receiver in the output circuit of a low power tube generator that can be tuned over a considerable range of frequency. The crystal is placed loosely between small metal electrodes connected to the tuning condenser, and the knob of the condenser is turned back and forth. Whenever the frequency reaches a point at which the crystal resonates, the piezoelectric action of the crystal sets up electric oscillations of crystal frequency, which are superposed on the frequency already present. They persist long enough to produce an audible beat note with the changing circuit frequency as the condenser is turned. A milliammeter in the output circuit will indi-

[29] R. W. Wood and A. L. Loomis, Phil. Mag. **4**, 417–436 (1927).

cate a sudden decrease in current at crystal frequency. Sometimes a click can be heard when a small X-cut plate, without electrodes, is simply laid on a binding post of the tuning condenser and the condenser is then tuned through the crystal frequency.

In this brief survey it has been impossible to do more than scant justice to a field in which more than a thousand articles have been published in recent years. It is hoped that the reader is at least convinced that piezoelectricity, far from being a narrowly restricted subject, is intimately related to all branches of physics.

Some General References

H. Geiger and K. Scheel, *Handbuch der Physik* (Springer, Berlin), Vol. 6, 13, 16, 24. Fundamental theory of piezoelectricity and of vibrating crystals.

L. Graetz, *Handbuch der Elektricität und des Magnetismus* (Barth, Leipzig), Vol. 1. Fundamental facts and principles.

P. Vigoureux, *Quartz Resonators and Oscillators* (H. M. Stationery Office, London, 1931). Physical properties of quartz; theory of resonator and oscillator.

A. Scheibe, *Piezoelektrizität des Quarzes* (Steinkopff, Dresden, 1938). List of all known piezoelectric substances; technic of measurements; data on various cuts, luminous resonators, frequency standards, and quartz clocks.

H. Pender and K. McIlwain, *Electrical Engineers' Handbook* (ed. 3, Wiley, 1936), Vol. 5. General statements concerning quartz, methods of cutting, etc.; oscillator circuits.

American Radio Relay League, *Radio Amateur's Handbook* (ed. 15, West Hartford, Conn , 1937). Good simplified treatment of quartz technic and oscillator circuits.

E. B. Moullin, *Theory and Practice of Radio Frequency Measurements* (ed. 2, Griffin, London, 1931). Performance and theory of quartz resonator and oscillator, based largely on Dye's investigations.

A. Hund, *High-frequency Measurements* (McGraw-Hill, 1933). Tests of resonators and oscillators.

Brush Development Company, *Brush Strokes* (Cleveland, O.). Issued periodically; data on Rochelle salt microphones, pick-ups, loudspeakers, filters, etc.

L. Bergmann, *Schwingende Kristalle und ihre Anwendung in der Hochfrequenz und Ultraschalltechnik* (Teuber, Leipzig, 1937). Technic of ultrasonic experiments.

Introduction of the Pressure Concept

Robert S. Shaw
Department of Physics, The City College, New York, N. Y.

ONE of the basic difficulties in general physics is the fact that the course embraces topics that show very little superficial resemblance to one another. The underlying unity is by no means obvious, so that one great aim in teaching must be to bring out that unity.

Most textbooks seem to ignore this aim in the treatment of the mechanics of fluids. No attempt is made to emphasize the view that this topic is simply a branch of mechanics, of which the student has already learned the fundamental principles. Instead, a new term, *pressure*, is dragged in quite arbitrarily, and some of its properties established only by independent experiments. This is entirely unnecessary and, I believe, undesirable, since the treatment of fluids as a special case under the general principles of mechanics leads naturally to the concept of pressure and to its properties.

One should begin the study of fluids at rest by reviewing the principles of equilibrium. The nature of fluids makes it clear that torque will not be a useful tool in the study. The next step should be the analysis of the hydraulic press as a simple machine. A small force f applied to a small piston of area a will yield a large force F on a large piston of area A. This, as usual, can be true only at the expense of distance, so that, if the point of application of the force F moves a small distance d, the force f must be exerted through a large distance D. The law of simple machines gives the relation,

$$fD = Fd. \tag{1}$$

Now, as usual, we look for a geometrical relation between the arbitrary distances and the dimensions of the machine. The obvious connection is the fact that the fluid displaced by one piston occupies the same volume as that which displaces the other piston. It is significant

that this is not true for compressible fluids, so that the discussion is now restricted to liquids. We can now write the geometrical relation,

$$aD = Ad. \tag{2}$$

When Eqs. (1) and (2) are combined in order to eliminate the arbitrary distances, we obtain

$$f/a = F/A. \tag{3}$$

Of the several forms in which Eq. (3) might have been written, we have chosen the one in which the left member refers to one of the pistons only, the right member to the other piston.

We now look at Eq. (3) to see what it tells us. It will give us the value of the mechanical advantage of the machine, of course, but it is more important to notice these facts:

(1) The quantity f/a enjoys a "conservation" property. This fact suggests the desirability of giving it a name. This criterion for giving a name to a quantity is sometimes also met in discussions of momentum. Briefly, when one applies Newton's third law to collisions, it turns out that the quantity mv is conserved; this quantity is then given a name.

(2) Pressure is not a strange concept but one that arises naturally when the principles of mechanics are applied to fluids.

(3) Pascal's law is not an independent generalization to be established only by experiment, but one that may also be deduced from the principles of mechanics. This puts the law in a proper perspective in relation to other laws.

(4) Perhaps pressure will be a more useful concept than force in the study of the mechanics of fluids. It will almost certainly be more useful in the study of liquids.

Once pressure has been introduced, authors generally deduce its properties from the principles of mechanics, although this practice is by no means universal. The two principal properties are the independence of direction and the relation of pressure to depth. These are commonly treated separately, the relation of pressure to depth being obtained by considering forces in a special direction. The restriction to gravitational forces results in a deduction which, though convincing, is not satisfying to me, or to some of my students. It is possible to deduce these two properties together in a somewhat artificial manner which has the merit that it involves forces that are not restricted to any particular direction.

Consider a cylinder containing some air and closed by a movable piston. Let the cylinder be supported in a liquid with the piston at a depth h below the surface of the liquid and the piston facing in any direction. By means of a hose it will be possible to introduce more air into the cylinder, thus causing the piston to move a small distance s. Since the distance is small, we may consider that the force acting on the piston has a constant value F. If the weight of the piston be neglected, the work done by the outside agency is Fs and results in the lifting of a volume As of liquid from the vicinity of the piston to the surface, A being the area of the piston. If ρ is the density of the liquid, the increase in potential energy is ρAsh. By equating work done to energy gained, we get the relation $Fs = \rho Ash$, or

$$F = \rho Ah. \tag{4}$$

We can now appeal to our previous conclusion that pressure is a more significant concept than force in the study of liquids to justify dividing by A; or we can strengthen that conclusion by analyzing Eq. (4). The force F is seen to depend upon two essential factors, ρ and h, and upon an arbitrary factor, A. Hence, although force is arbitrary, F/A is not. The more important aspect of this method of deducing Eq. (4) is the *direct evidence* that the force involved acts upon an area oriented in any direction. Of course, the force given in Eq. (4) is really the oppositely directed reaction to the force exerted by the liquid.

It seems unfortunate that texts so seldom take advantage of this opportunity to emphasize the essential unity of physics in connection with the topic of mechanics of fluids. If mechanics itself is not presented as having unity we fail to lay the best foundation for teaching the more general unity among physical phenomena.

The Role of the Sciences in General Education*

DUANE ROLLER
Department of Physics, Hunter College, New York, N. Y.

ALTHOUGH the sciences have long had a place in the college curriculum, the role which they should be called upon to play today is immensely more prominent and significant than ever before. The public is, today, thoroughly aware that our culture in its material aspects has been profoundly affected by technologic advances and that we are continually facing problems of how best to utilize the results. Less generally or consciously understood, however, is the radically new character of many of the ideas and concepts that have long been emerging from the sciences, and the extent to which they are in serious conflict with traditional beliefs held precious by many persons. Yet we must face the expectation that it is by these new views that our culture eventually will be dominated. Still less generally appreciated is the extent to which the tested methods and technics of the sciences provide the general public with the means for attacking a large variety of problems with confidence and efficiency, and how highly probable it is that these scientific procedures will eventually be utilized to solve many of the crucial problems of living. To the scientist, on the other hand, all this seems obvious, although he is just beginning to take it into full account in planning his science courses for the general student. When college and school administrative bodies understand it more thoroughly, we may expect a whole-hearted and vigorous effort on their part to help place the sciences in the important place they must occupy in any program of liberal education that is truly modern.

In the attempt to devise programs adequate for our rapidly changing society, many teachers in the sciences are examining the aims they are pursuing and the effectiveness of their methods. Many problems are presenting themselves, but the insight already gained into them is evident in the modifications in curriculums and in instructional procedures being tried in various colleges. Out of this renewed activity there is almost sure to evolve a kind of science instruction that will be of extremely great value to youth approaching the responsibilities of citizenship in our modern society.

EARLY SCIENCE INSTRUCTION

In seeking to understand the character of our present college science programs and the causes of the confusion existing about them, it is helpful to recall some of the early history of science instruction in this country. The instructional programs of today naturally have been built up by utilizing the tested purposes and practices of a particular period, and by adding new ideas and practices to them. Since we shall concern ourselves here with science instruction for the general public—as differentiated from that for professional scientists and technologists—no particular distinction will be made between the developments in the lower division of the college and those in the secondary schools. The interplay of the trends on these two levels renders such a distinction difficult and is, in itself, significant.

The earliest science instruction in this country, from about 1750 to 1880, tended to be utilitarian and descriptive in its aims. Chemistry and botany, for example, were first taught on the college level in medical schools, in connection with *materia medica*. The emphasis in botany was on plant classification. The other science courses were similarly organized to present facts, but with little attention given to relationships. Much of the learning was by rote. A strong religious note was in evidence, particularly in astronomy, geology, and biology. Today we can still find tendencies that grew out of these early utilitarian, descriptive, and religious aspects of science teaching—in the emphasis that is placed on practical applications; in the tendency still evident in some departments to teach isolated facts and test student retention; in the efforts in some institutions and on the part of some

* This paper is devoted mainly to a description of trends in science instruction in the lower division of the college as they are reflected in recent articles and books. It is based on a paper read by the author at the Institute for Administrative Officers of Higher Institutions, University of Chicago, July 13, 1938.

individuals to use the sciences to demonstrate the workings of a divine providence. Science instruction in the earliest period doubtless gave the student an acquaintance with natural phenomena, particularly in their relation to the practical aspects of life, but the objectives and methods did not encourage much independent and original thinking.

It was near the end of this early period, in 1862, that Congress passed the act which granted large areas of public lands to the several states for the establishment of agricultural and mechanical colleges. Although the extent to which this act fulfilled the intended purposes is well known, its importance for our present considerations is that, in every instance, whether in strengthening an old institution or in founding a new one, it was the most scientific education that reaped the largest benefit; scientific education was given the greatest stimulus that it had received up to this time in the United States.[1] In botany, for example, the result was the gradual development, particularly in the agricultural colleges, of a battery of strong technical courses. In these institutions, at least, there began to be some realization of Huxley's dream of science as "a foundation of education instead of being, at most, stuck on as a cornice to the edifice." Incidentally, from this highly technical work in all the biological fields, facts and generalizations of the greatest value for the purposes of a modern liberal education have been continually emerging; but it is only very recently that a really serious and systematic attempt has been made to adapt this important material to the needs of the general student in the school and college.

During the second of the historical periods which we are considering—from about 1880 to well after the beginning of the present century—we find the utilitarian and religious aims beginning to give way to that of "training the mind." It began to appear that the sciences offered unique possibilities for giving training in observation, mental concentration, and the like. The ability of the student to bring previous experience to bear on new situations presumably could be trained by exercise in the logical disciplines. Science courses thus were gradually made more systematic and formal, with the subject matter presented deductively and its logical organization stressed. Drill on factual material continued, partly because this appeared to offer training for the memory.

A significant advance, especially evident and possible in the physics of this period, was the introduction of more of the genuine experimental and theoretical aspects of science, with less stress on mere phenomenology. In the biological sciences, anatomy was beginning to receive attention along with classification, although the courses were in this respect still two decades behind those in Europe. Yet another two decades had to pass before physiology began to find a place in the courses, so influential had the evolutionary theory become in concentrating the attention of biologists on structure. This influence appears to have lasted even to the present day.

It was also in this second period that the laboratory came into vogue in this country as the agency needed to make science instruction more vital and effective. Laboratory experiments were devised to give training in deductive reasoning, in forming systematic habits of work, and in observing and reporting phenomena accurately and neatly. Individual interests and needs could be disregarded, since all students were presumed to possess mental faculties in common which needed to be trained. Students who were seeking general culture were given the same preliminary scientific training as those who intended to pursue scientific careers.

Scientists who wished advanced training during this period went abroad or else were self-taught. Those who returned from abroad naturally reacted against the superficial and dilettante work carried on by their less well-trained colleagues. There was much provincialism and wasted effort; a continuity of tradition, training, and learning was lacking in our laboratories and universities. If a respected place in the scientific world were to be gained, an understanding even

[1] F. W. Clarke, "A Report on the Teaching of Chemistry and Physics in the United States," *Circular of Information of the Bureau of Education*, No. 6–1880 (Washington: Government Printing Office, 1881). Clarke lists 117 textbooks relating to physics and 211 to chemistry in use in this country by 1880. Most of these were written abroad. Of the books on chemistry, about 40 percent dealt with general chemistry, about 16 percent with qualitative analysis, and only about 3 percent with organic chemistry.

of the meaning of genuine research had first to be developed and then intense efforts toward productivity fostered to the utmost.

Similar to this was the situation in all the sciences until near the beginning of the present century. Yet for a number of years now, and even preceding the present unsettled conditions in Europe, we have been leading the world in more than one field of scientific productivity. This rapid and enormous progress has had its price, although it is a price that most of us have willingly seen paid. The encouragement and maintenance of vigorous programs of research in our higher institutions need no defense, although both scientists and college administrators should be willing to promote a general understanding of the role of the sciences in human life that will enable the public to support research on its own merits. The successes of scientific research constitute some of the greatest accomplishments of American education, not alone because of the resulting advances in the sciences, but because of their far-reaching influences on American thought, and individual and social life. Yet it must also be recognized that this preeminence has involved sacrifices. We have had to forego some of the most important, original aims of the liberal arts colleges. We have often diverted our most able personnel to research, and have had to let teaching in the college suffer by basing promotions and awards solely on research productivity. Great rewards for research must, of course, be continued, particularly in the university and upper division of the college; but it is of significance that certain higher institutions and organizations of scientists have recently created special awards for outstanding contributions in college teaching. We must not forget, either, that both research and teaching have suffered because very able men have been diverted from these activities by the disproportionate rewards given for administrative work.

The situation in the sciences was also aggravated because of the fact that our undergraduate instruction was patterned somewhat after the English system, with perhaps an overemphasis on the nonscientific, Platonic tradition, whereas our graduate work came under the German scientific influence. It is from inharmonious combinations such as these that our future system of science education in the liberal arts college must be salvaged.

The Last Thirty Years of Science Instruction

A reaction against formal discipline began to appear in about 1910, and the trend was again toward the utilitarian and informational aims of an earlier time. But now there was also an emphasis on the newer developments of science. Radioactivity, x-rays, and the electron were becoming matters of common talk; quantum theory and relativity were beginning to produce changes of a profound character in our physical concepts, and were eventually to bring into question even our theory of knowledge. A modern industrial society created chiefly by physics and chemistry was beginning to make itself felt, and the need for having the sciences play a more active role in the lives of students was receiving general recognition. At the same time, enrolments were increasing rapidly, and even the colleges were now becoming institutions for all the people. So-called general science began to appear in the secondary schools and, because it was new and relatively free from some of the older traditions, gained popularity at the expense of some of the older sciences. A notable trend was toward a synthesis of botany and zoology, with increased emphasis on physiology and ecology. Such syntheses of fields for instructional purposes have seldom been approached in a dispassionate way, however. Thus, many of our present-day elementary biology courses appear to consist chiefly of zoology; but the reason for this does not seem to be based so much on considerations of what should be involved in a liberal education as on the fact that such an emphasis has proved efficacious in attracting premedical students.

So far as their *stated* aims and functions are concerned, the liberal arts colleges have leaned during the past three decades toward generalized social objectives without emphasis on specialization. But between these stated aims and the actual college offerings the disagreement is often considerable. The science courses, and others as well, have usually been arranged in sequences

suitable for specialization in major fields and a chief objective has been to select and prepare the most able students for admission to graduate study. This is, indeed, a most important objective but, according to the stated aims, not the only one.

In the secondary schools, the trend has been toward a more functional approach in science instruction. In the decade after 1920, following the influence of the Cardinal Principles of Secondary Education, the tendency was to organize and teach the sciences so as to contribute to such human activities as health, vocation, citizenship, and worthy use of leisure. For the achievement of these so-called "ultimate objectives," various technics, such as the "project method," were proposed.

Most of the elementary courses of today are still a mixture of the accepted practices since 1880, and of the newer ideas of showing the students the importance of the sciences in modern life and imparting to them useful scientific information. The desirability of having definite and explicit teaching objectives is coming to be realized, although teachers are finding it difficult to state their objectives and there is, as yet, little general agreement as to what the objectives should be.[2] Considerable emphasis still is placed on "covering ground," without reference to the functions of the content in orienting the student. A course intended for the general student is often little more than a very abbreviated treatment of the elements of the science itself. A forward step, evident in a few courses, is the tendency to organize the subject matter and experiences about major concepts that are significant for a liberal education, rather than about those generalizations of the pure sciences that are important mainly as a means of organizing the knowledge of the scientist.[3] Other significant trends include a wider use of the problem method of development, more attention given to evaluation and tests,[4] and an increased use of lecture demonstrations, science museums, and other visual aids.[5]

Our brief historical sketch perhaps has served to indicate that certain persistent demands are being made on the whole science program for the general student; and that these have been the result mainly of the impacts of the sciences on human living, of a changing psychology, and of an increasing and changing school and college population. Along with these we must take into account a new conception of the functions of education for modern living and its implications for the science program.

New Conceptions of a General Education

A part of the present dissatisfaction with the established educational system is, of course, a consequence of the phenomenal increase in the percentage of youths attending school and college, and of older people seeking adult education. Conventional curriculums, found to be unsuited to the needs of many of these students, have led to bewilderment and boredom, rather than achievement, with resulting discouragement, lowered standards, and other undesirable consequences. Vocational education has not proved itself a remedy for this situation. There is a growing feeling that even "nonacademically minded" students need to be taught something more than how to earn a livelihood. Moreover, rapid technologic and social changes have resulted in marked vocational instability, so that the need is for training that will provide vocational versatility and the capacity for the flexible meeting of changes.

But the problem is larger even than this and concerns all students. The traditional liberal arts programs were reasonably satisfactory for the types of students they served because such agencies as the family, the church, and the community proved efficacious in introducing each new generation to the accepted ideas,

[2] An investigation made by the Botanical Society of America revealed a great diversity of opinion among botanists with respect to the objectives for a general course in botany (C. W. Horton, unpublished data). A similar investigation involving all the sciences is now being made by a committee of the American Association for the Advancement of Science; see P. B. Sears, Science **87**, 506–7 (1938).

[3] National Society for the Study of Education, *31st Yearbook* (1932), Part I.

[4] A nation-wide testing program in college chemistry, similar to that which has been carried on in physics since 1933, was instituted in 1936 by the Division of Chemical Education of the American Chemical Society.

[5] An excellent, documented account of trends in science teaching in this country and their implications for general education appears in *Science in General Education* (Appleton-Century, 1938) by the Committee on the Function of Science in General Education of the Progressive Education Association. This significant report is the result of a thoroughgoing study of the problems of teaching the natural sciences in relation to the purposes of general education.

beliefs, and practices of our culture.[6] But today many of these conceptions, and the sanctions behind them, are being assailed, or even destroyed; and the older cultural agencies are proving ineffective and incompetent in utilizing modern knowledge to help youth to understand itself and its environment.

The more obvious social and technologic trends involving alterations in our industrial and living conditions have received wide discussion, but the present rapid shift in our culture is much more fundamental than this. It involves our patterns of thinking and values, as these have been affected by changing conceptions of the scheme of nature and man's place therein, and of the individual and his relations to society. Our picture of the physical world has changed radically. Conceptions of human behavior, disease, and organic needs are under revision. Insight into human nature and conduct has greatly increased. Our ideas of possible forms of family and social relationships are widening. Large and important areas, even in the sciences themselves, have scarcely been touched by the shifting pattern of thinking that is emerging from physics—discontinuity, relativity, operationalism, uncertainty, non-Aristotelian logic.

The task is not only to inculcate these emerging concepts that are to dominate our new culture, but actually first to formulate them; that is, to interpret their human meanings and emotional significances. To the archives of modern scientific research we must look for the basis conceptions that will yield a world-view free from major paradoxes; for an enormously increased time perspective; for understandings that are contingent and approximate, and involving processes functional and evolutionary; for tests and safeguards of valid and creative thought. There will be nothing static about this new formulation, for it will be subject to the continuous revision so characteristic of scientific thinking and procedures.

It is not implied that human and social problems will thereby necessarily cease to be *value* problems, to be handled solely by the objective and detached methods of the sciences. It is for the *basic* ideas and beliefs that we must go mainly to the sciences, whose advances are responsible for the disintegration in the older framework. The latter was the product of the best available knowledge, investigation, and speculation of its time; and it seems apparent that the basic modern conceptions, which we are to render meaningful and congruent, must likewise be drawn from and supported by the best scientific research of our present age.

In the light of the foregoing considerations we can draw some tangible aims for science instruction. The situations and problems with which the modern individual must deal obviously arise out of his personal contacts, his conceptions of the world and man, his needs for physical and mental health, and recreation, and his relationships with the economic, governmental, and educational systems. If these situations and problems are to be dealt with adequately, we must draw heavily on the sciences for material that will develop in the individual such abilities and traits as careful and critical methods of thinking, continuing interests in those aspects of culture and activity of major importance in our civilization, insights based on the major generalizations of the pure sciences themselves, certain valuable attitudes and appreciations, recognitions of values and standards, activities creative in character, and effective emotional orientation and control. The specific scientific skills and information that may be considered as most important for a liberal education are those that will contribute to the aforementioned human abilities and traits.

As this reformulation of material for instructional purposes progresses there will be less excuse than ever for any failure to award the sciences the place and the time they deserve in college and school curriculums. If we have correctly interpreted cultural origins and trends, and the demands on the individual in our modern society, it will not be enough merely to give students some opportunity "to learn a little about science." Science instruction, instead, must eventually come to be recognized as a truly basic and integral part of the general training of every citizen, no matter what his vocation or profession may be.

[6] For a more extensive discussion of some of the points of view reiterated here, see L. K. Frank, "The Task of General Education" and "General Education Today," Social Frontier **3**, 171–73, 209–11 (1937).

Agencies of General Education

The efforts that are being made at the present time to develop science courses suitable for the purposes of general education are admittedly exploratory and experimental. The general problems involved are gradually becoming clear, however, and the various means of evaluation now under development will reveal the extent to which we are arriving at their solutions.

At the present time, survey courses are the most widely used agencies of general education. A *survey course*, as the term is now usually employed, is any course intended for college underclassmen, primarily as a part of their general education, which cuts across traditional course lines and presents an integrated picture of a whole field of knowledge.[7] The first course of this kind in the sciences appears to have been given at Dartmouth in 1919, and the first comprehensive program involving more than a single survey course was established at the University of Chicago between 1923 and 1925. Although the earliest survey courses were in the social studies, at the present time more colleges —approximately 150—offer such courses in the sciences. A few colleges are offering composite courses which include the humanities, the social studies, and the sciences in a single course.

Existing survey courses in the sciences appear to fall into one of two groups.[8] In one group the sciences involved are kept more or less distinct, the emphasis being on an overview of these sciences and an insight into their achievements. In the other group, the emphasis is on broad generalizations that serve to associate ideas from various sciences according to the manner in which they occur in life situations. An analysis of the treatment of subject matter of the courses in both of these groups reveals three pairs of contrasting emphases.[9] A particular course may emphasize the sciences for their own sake; or it may interpret them as they affect human affairs of general interest or concern. It may provide an extensive survey of a broad field of knowledge; or it may be limited to a more or less intensive treatment of selected topics and principles. It may be analytical, with the emphasis on relationships; or it may be descriptive, presenting information without much attempt to show relationships. Any course can be classified in terms of these three pairs of characteristics. For example, the survey courses in the physical and biological sciences at the University of Chicago and at Columbia University tend to be of the pure science-comprehensive-analytical type; the physics-astronomy course at Ohio State University tends to be pure science-selective-analytical; the physical science course at Pasadena Junior College is interpretative-selective-descriptive.

Which of these various emphases are the better depends upon the functions of the course. Here again we recognize the importance of deciding just what it is we want our courses to do to the students, which means, in the present case, deciding what constitutes necessary and valuable behavior in our modern culture. If we have been finding this difficult, doubtless it is largely because we have never before really tried to state our objectives explicitly. To frame some of the more important objectives of a science course and obtain fairly general agreement on them does not appear to be so difficult, once the need for having these objectives is fully appreciated.

As a result of the criticism that underclassmen do not have enough background to profit from survey courses that cut across present areas of knowledge, several colleges have instituted upper-division "correlation courses." Their purpose is to aid the upperclassman in integrating knowledge in the fields which he has already studied in part. At least one institution—the University of Louisville—employs both survey and correlation courses; a senior who has majored in zoology, for example, is required to take a correlation course that includes all the sciences.

Many scientists have been skeptical or frankly critical about the trends that are evident in some survey courses and in the textbooks that have been prepared for them. They point to the danger, or futility, of stressing social implications to the point where the course contains

[7] *What About Survey Courses?* Edited by B. L. Johnson (Holt, 1937). This book provides a comprehensive discussion of existing survey courses and programs in American colleges. The chapters dealing with survey courses in the sciences were prepared by R. J. Havighurst, S. R. Powers, and F. L. Hovde.

[8] Reference 7, pp. 214–19.

[9] R. J. Havighurst, Am. Phys. Teacher **3**, 97–101 (1935).

very little science, or offers few of the unique educational advantages of the sciences; of attempting to achieve teachability by omitting everything that requires student effort, and sacrificing or even showing disdain for accuracy of scientific statement; of resorting to mere description at the expense of analysis; of spreading out material so thin that one wonders how it can possibly affect student behavior or result in anything more than an attempt to "cover ground." Yet it must be remembered that these early efforts are guided by worthy motives and that they are pioneer in character. Not passive skepticism, but the assistance and sympathetic cooperation of a larger number of competent scientists is the evident need.

Another criticism concerns the question of whether the most effective approach to certain important aspects of a science-made culture is possible unless the student has a rather thorough understanding of the main aspects and the essential methodology of at least one of the fundamental sciences. Few would contend that this need be the kind of mastery and working knowledge of the science that is required of the prospective scientific specialist; much of the scientific knowledge of the average non-science major will necessarily be superficial, as is much of the useful knowledge that all of us possess in fields other than our specialties. But there may be important educational advantages, some of which appear to be exemplified in the successes of the special sciences themselves, of confining the scientific core of some cultural courses to the domain of a single fundamental science, or even some important division of it. Possibly many of our existing, conventional courses in the special sciences and their branches could be adapted with great success to the needs of the general student, now that experience with survey courses has helped to clarify our conceptions of a general education program. The point to be emphasized is that the comprehensive survey course involving core material from several sciences is only one of various possible agencies of general education. The mere inclusion of several sciences certainly is not sufficient, and for the realization of a number of important objectives may be neither necessary nor desirable.

Some college survey courses patently are introductory and elementary in character, the inference being either that the students entering them know next to nothing about the simplest natural phenomena and everyday applications of the sciences, or else that they must be retaught these elements in the new settings more appropriate for the cultural purposes at hand. This doubtless indicates that much that is now being tried in the colleges as a pioneer venture will eventually find its rightful place at the secondary level. In fact, some senior high schools already are experimenting with survey courses. The indication is that there will be serious overlapping unless the colleges seize this opportunity to develop cultural courses that are on a genuinely higher level of student maturity.

Special opportunities exist at the more mature level for giving students insight into our culture as it is affected by the various attitudes and processes constituting scientific method, and by the underlying philosophies of the sciences. Although development of the ability and disposition to think reflectively is an objective that eventually we must come to regard as of great importance in all science education, unique opportunities for helping to realize this objective are evident at the college level. Important problems can be considered that have particular significance for older students. Increased emphasis can be placed on problem-solving through reference to books and similar standard sources of information, as the student will by this time have had considerable practical experience and first-hand knowledge of the phenomena involved. Moreover, it is at the college level that a conscious awareness of the processes involved in reflective thinking, and of the advantages of an understanding and proper use of language, is likely to be most effective in improving thinking, since the student should by then have had varying experiences, at the lower levels, in actual problem-solving. To set up such aims as educationally realizable is in good accord with recent psychological theory[10] and does not represent a return to the older faculty psychology, with its emphasis on the disciplinary value of subject matter that is merely logically ordered. The implication of the present aims is that scientific attitudes and methods are not confined in their applicability to the sciences, that activities in the sciences differ from those of everyday life mainly in their primary concern with the extension of knowledge and the refinement and control of methods, rather than with achievements that are immediately and practically useful. Thus to give the student a thorough appreciation of the applicability of scientific methods to a great variety of problems is a most important contribution that the sciences can make to his general education. Physical science, particularly physics, has an especial contribution

[10] Reference 5, Chap. VII. This chapter contains an excellent discussion of the teaching of the sciences in ways to encourage reflective thinking.

to make here. It can show how the simplest forms of classification and of causal relationships are recognized, how precise descriptions of relatively simple objects and processes are attained, how more abstract terms may be introduced to effect economies of thought and communication, and how the maintenance of precision of this kind is of crucial importance in all communication, as well as in other sciences where the phenomena studied are less sharply distinct and the problems of precise statement more difficult.[11]

Role of the Laboratory in General Education

A defect in science survey courses that has been generally recognized is their apparent failure to give the student adequate physical contact with the phenomena studied; his knowledge, therefore, is likely to be highly verbal and intellectual, and not enriched by emotional understanding. This has been used as an argument for including laboratory work, which is missing from some of the present survey programs. But there are other and, perhaps, better arguments. Such a laboratory must indeed be one that is designed specifically for cultural purposes. It must not be concerned with those experimental technics that only the specialist is likely to need, or with the mechanical performance of experiments merely to get results expected. The development should be along broad lines that bring the student to realize how the essential strength of the scientific way of doing things lies in a continual resort to experiment, and how it is only through the constant interplay of experiment and theory that the sciences have obtained their enormous successes.

Such laboratory work could also be expected to give the student guidance in how to look for things, and for what to look. Unlike lecture demonstrations, it could provide opportunities to observe more than is simply pointed out, and to carry into practice procedures suggested by observation and thought. It need not be merely amusing, but it should be made pleasurable and a source of real esthetic satisfaction. To have such laboratory work for cultural purposes is not an idle dream,[12] but it requires careful planning and much trial.

[11] J. Pilley, Am. Phys. Teacher **6**, 218 (1937).

[12] See, for example, H. I. Schlesinger, "The Contribution of Laboratory Work to General Education," J. Chem. Educ. **12**, 523–28 (1935); a digest of the article appears in Am. Phys. Teacher **4**, 55 (1936).

An objection often voiced to laboratory work in an elementary course is that it is inefficient in its utilization of student time and effort. Inefficient in terms of what? In the case of those objectives that can be realized about as well, or better, through reading, lecture demonstrations, museum exhibits, and similar visual aids, the laboratory certainly would prove to be wasteful of time, effort, and money. But if this root of the sciences, the laboratory, can also make unique and important contributions to the general education of the individual, then it should be maintained as an instructional device for the realization of these unique objectives, and its efficiency measured only in terms of them. It is an illusion that an hour spent in the laboratory or in field work is necessarily of less educational value than the same time spent in some other kind of study.

Some Implications for Teacher Preparation

The foregoing considerations seem to have some clear implications for the kind of teacher-preparation that is desirable for efficient teaching and participation in the other activities of a program of general education. That the colleges will eventually provide specially selected and trained instructional staffs must be assumed, for a cultural program of the kind envisaged calls for teachers of superior qualifications and experience who have a primary interest in this level of work. No very important place exists on such a staff for underpaid apprentices, the deadwood of the college faculty, or even able scholars who seek a mere stepping stone to something that seems better.

The prospective teacher should expect to acquire a general cultural background from his undergraduate courses in the humanities, the social studies, the fine arts, and the sciences. This part of his training should also provide him with conceptions of sound scholarship in these fields, and with a basis for developing clear appreciations of their contributions to our culture and to the solution of personal and social problems. So broad an outlook will be increasingly easy to acquire, since teachers of the future will themselves participate as students in a modern program of general education.

A point on which there is universal agreement is that a college teacher must know his subject matter. A teacher of a science must be a scientist. He must have intensive and extensive training, of graduate caliber and involving genuine research experience, in one of the fundamental sciences. A much wider training in cognate scientific fields is needed than heretofore, but this does not seem to present unsurmountable difficulties; adequate preparation in a fundamental science involves a considerable amount of work in bordering fields.

Nothing appears to be so broadening, scientifically, as a thorough and explicit knowledge of the methodologies and underlying philosophies of the sciences. Much more attention doubtless should be given to this aspect of training than heretofore, particularly since increasing emphasis is being placed on it in the education of the general student. Also of evident importance is the historical aspect of science. This should no longer be a mere chronicle of men of science and their achievements, as is the traditional history, but a history of science that traces the growth of ideas and procedures, and that recognizes the sciences as primarily "a social outgrowth toward social ends."

Agreement would be found to be surprisingly general, I believe, that a sound knowledge of modern psychology and its applications to education is highly desirable equipment for any teacher in the lower division of the college. Indeed, to assert that a teacher should not make use of the best available knowledge of the workings of the human mind would be stupid, and counter to the whole spirit of the sciences. Since our prospective teacher will be neither stupid nor unscientific, he will seek instruction in educational psychology, provided it is made considerably stronger, broader, and more modern than is most of the present instruction in this field. An opportunity for practice teaching would also be welcomed; it doubtless should come during, or after, the period of graduate training, and must be under the supervision of competent and experienced teachers of the sciences. To make such teacher-training courses compulsory would be dangerous, and for obvious reasons. Instead of trying to make their courses compulsory for college teachers, the educationists should concentrate their energies on developing a small number of courses of such marked excellence that no prospective teacher could afford to miss them.

The completion of so ambitious a program of teacher-preparation during the period of formal training is hardly possible. Nor is it desirable, since there must be provision for the continual growth of the teacher in service. In this connection, attention should be directed to the idea of having summer "workshops," where teachers from various colleges can meet for informal discussion and study of their instructional problems. Also of importance here is the whole question of the relation of teaching and research in the lower division of the college, especially in the junior college, which is isolated not only from the graduate school but even from the college as a whole. As has been said elsewhere many times, it appears that a teacher cannot continue to grow or be anything more than a purveyor of a fixed body of knowledge unless he participates actively in creative work related to his field. Another way to put this is that constant mastery of any broad field of intellectual endeavor, including teaching itself, inevitably involves continual recognition of new lines of investigation and new angles-of approach, with the result that the individual has a constant urge toward creative work which must be satisfied. Continued mastering of a field, inherent in the best teaching, and creative work in the field are essential aspects of the same process. If this is true, then the relation between creative work and all good teaching is clear. Since such creative work is not to be carried on simply for its own sake, it may be greatly varied in character and in degree of pretentiousness, can be adapted to local circumstances and facilities, and will always be connected fairly intimately with the other institutional activities of the teacher.[13] Although all this may seem obvious, the fact remains that there is no genuine recognition of it in a great many of the colleges. Yet such recognition is a matter not so much of large material resources or of unusually small teaching schedules, as of creative atmosphere sustained in an able faculty through proper attitudes and emphases.

[13] See, for example, R. L. Jeffery, Am. Math. Mo. **42**, 364 (1935).

This brief review of what appears to be some main trends in the organization and content of the sciences in the lower division of the college points to types of teacher-preparation and teacher-service that are comprehensive and exacting. A very important question remains. Will the colleges and their science departments be able and willing to attract men and women into lower-division teaching who have the personality, ability, training, and wisdom needed to carry out a modern program of general education that has its essential basis in the sciences?

College Physics as a Requirement for Entrance to Dental School

EUGENE W. SKINNER
Northwestern University Dental School, Chicago, Illinois

THE question of the requirement of a course in physics for entrance to dental school is controversial among dental educators. At the present time, 24 of the 40 dental schools in the United States require 6–8 semester credits in college physics. In the cases where physics is not required, the reasons given by the administrators are interesting and perhaps instructive, but represent a point of view that many teachers of physics are likely to question.

At the outset, it should be stated that physics is of great importance to dentistry, particularly in its operative phases. An entire article might be devoted to the elaboration of this point.[1] Suffice it to say, that every operation performed by the dentist involves one or more principles of physics: in every filling placed in the tooth, in every oral diagnosis, in every tooth straightened, and in every set of false teeth placed on edentulous gums. Probably in no other profession, aside from engineering, is a knowledge of physics of more importance than in dentistry.

In order to explain the attitude of some dental educators in regard to the course in college physics, it will be necessary to summarize the events which have transpired in dental education during the last seven years. During this period, dental teachers and administrators have been very active in the study of the aims and curricular content of the dental schools. The entire field of dental education has been scrutinized and surveyed with a thoroughness probably unparalleled in professional education. The work was carried out by over 100 teachers of dentistry, their efforts being coordinated and directed by a professional educator who is well known for his sane viewpoint in education. The study has been made possible by a grant from the Carnegie Corporation of New York. To date, $45,000 has been granted. Teaching methods are under study at the present time.

The first part of the work culminated in the publication of a report[2] which is very extensive in that it not only analyzes oral health needs and aims of dental education but sets forth suggested courses of study for every subject in the dental curriculum.

In 1934, the Curriculum Survey Committee presented a number of resolutions at a meeting of the American Association of Dental Schools, and, after considerable discussion, they were adopted. The resolutions[3] which are relevant to the present discussion are as follows:

(1) That a minimum of 2 years' study in liberal arts be required for admission to the dental school.

(2) That a minimum of 6 semester credits in general chemistry and 6 credits in biological science be required in the pre-professional course, and that studies in English, sociology, economics, and psychology be recommended.

(3) That the undergraduate dental curriculum be a 4-year course.

---

[1] E. W. Skinner "Physics for the Predental Student," Sch. Sci. and Math. **31**, 431–38 (1931).

[2] Curriculum Survey Committee, *A Course of Study in Dentistry* (American Association of Dental Schools, 311 E. Chicago Ave., Chicago, Ill. 1935), pp. 93–96.

[3] Am. Assoc. Dental Sch. Proc. **11**, 98 (1934).

The first and third recommendations went into effect in the autumn of 1937, and are binding on all dental schools in the United States and Canada.

The second resolution is interesting in that physics is not even mentioned. There are several reasons for this. In the first place, the voting members of the Association were strongly influenced by several prominent deans of schools of education who addressed the assembly during this period. Their argument was that the two predental years should be left free of professional requirements, in order that the educational program of the junior college might proceed unhampered. This argument was very convincing to the dental educators inasmuch as the initial motivation of the minimum two-year college requirement was a sincere effort on their part to raise the standards of the dental profession by requiring a broader general education.

The prescription of pre-professional subjects in the junior college to the exclusion of the social sciences and languages is further complicated by the fact that several states have prescribed certain predental subjects by law. The prescriptions are usually: physics, 6 credits; English, 6 credits; chemistry, including organic, 12 credits; and biology, 6 credits. In order that their graduates may be accepted generally in this country, about one-third of the dental schools have adopted this schedule. It may seem that chemistry is overemphasized, but it must be remembered that physiological chemistry is as necessary to the modern dentist as it is to the doctor of medicine; obviously, courses in general and organic chemistry are prerequisite to the study of this subject.

Assuming that the prescription of 30 semester credits out of a minimum required total of 60 is acceptable, many of the dental educators still objected to the inclusion of physics. The general impression was that the majority of the existing physics courses required 10–12 credits instead of 6; and, with college mathematics as a prerequisite, the total requirement for this subject would amount to 16–20 credits.

A recent study of suitable physics courses demonstrates, however, that such is not the case. Of 74 representative liberal arts colleges and universities selected at random, 61 percent were found to offer courses that involved only 8 semester credits, and 24 percent, courses that involved 10 credits. Of the remaining 15 percent, a few offered courses of 6 credits, and the rest, 12-credit courses. Approximately 35 percent of the total number required college mathematics as a prerequisite. By a coincidence, many of the physics departments which offered only the longer courses with a mathematics prerequisite were located in universities with dental schools, a fact that may explain the previously mentioned opinion among some of the dental educators.[4]

The dental educators[5] were also of the opinion that the average course in college physics contains extraneous subject matter which is of little use in dentistry, and that the teacher of physics favors the pre-engineering and physics major students to the exclusion of the predental students, as evidenced by the fact that more predental students fail in physics than in any other college subject. Despite these objections, all dental teachers are cognizant of the need for the study of physics in connection with dentistry; and the incorporation of a course in physics *in the dental curriculum* was therefore proposed. An outline of such a course is presented in the report previously mentioned.[2]

A comparison of this outline with the subject matter contained in a well-known physics textbook shows that 82 percent of the material in the textbook is included in the outline for the physics course recommended for the dental curriculum. Aside from specific dental applications, a few physical phenomena not ordinarily included in the college physics course, such as plastic flow of solids, elementary phonetics, and a somewhat detailed treatment of osmotic phenomena, were recommended for the dental course. The parts of the college physics course either omitted or little emphasized were principles of gravitation, hydraulics, meteorology, radio, and diffraction of light. Obviously, all of these omissions are unjustified, both from a cultural and practical standpoint. Furthermore,

[4] It should be noted that the discussion deals solely with the *minimum* requirements of 2 years in liberal arts. Obviously, the student should be encouraged to obtain a baccalaureate degree before entering dental school. In such case, he may elect more extensive courses in both mathematics and physics.

[5] Am. Assoc. Dental Sch. Proc. **11**, 32 (1934).

it is not feasible to introduce a course in physics into an already overcrowded dental curriculum.

On the other hand, there may be some justification for the opinion that the physics teacher may be consciously or unconsciously prejudiced against the predental students in his classes. Discussions with many physics teachers tend to substantiate this opinion. The author pleads guilty to such a feeling some years back when teaching physics in a liberal arts college. When these same students reach dental school they are neither better nor worse than the general run of liberal arts students.

Table I represents a comparison of the predental physics grades of 87 students with the grades obtained by the same students in "Dental Materials," a dental course taught by a physicist and essentially a course in physics as applied to dentistry. The grades in this dental course are typical of the achievement of freshman and sophomore dental students. The 87 students matriculated at Northwestern University Dental School from 68 colleges or universities, and

TABLE I. *Comparison of grades in physics and in "dental materials."*

Dental Materials Grades	Physics Grades				Total, Dental Materials
	A	*B*	*C* or *D*	Not Passing	
A	2	1	3		6
B		9	10	1	20
C	1	9	42	4	56
Not Passing		1	3	1	5
Total, Physics	3	20	58	6	87

represent the total number of students from the present freshman and sophomore classes who had elected physics in their predental work. (Physics is not required for entrance to this dental school at the present time.) Because the grade of *D* is not recognized in the dental school, the *D*-grades in physics have been included with the *C*-grades. Seventeen of the 58 physics grades appearing in the fourth column were *D*, and they are also included in the 56 grades of *C* given in dental materials. In other words, *all* of the students having a grade of *D* in physics received a grade of *C* in dental materials.

As may be noted from the table, the totals represented in the last row and column, respectively, are in good agreement. Furthermore, 54 (62 percent) of the grades are identical. Further comparison shows that 18 students received higher grades in dental materials than in physics (in addition to the 17 students of *D*-grade in physics who were raised to a *C*), in contrast with 14 students who received lower grades in dental materials than in physics. Had there been a *D*-grade, approximately 6 of the 42 students who received *C* in dental materials would have rated *D*. Although the students showed a slightly higher standard of achievement in the dental course than in physics, the difference is so slight that it is doubtful whether it is significant beyond the indication of a trend.

Reasons for a better achievement in dental school, if it exists, might be a greater interest and a clearer objective. Some dental students take their predental work grudgingly, only to meet a requirement. Consequently both interest and ambition are lacking, a condition for which the student is not always to blame. Such a condition reacts upon the instructor in some cases and results in a conscious or unconscious lack of sympathy toward such a student, whereas even one personal conference on the importance of physics for his future work might arouse his interest at least to a point where he would function as a normal student. We must recognize that the academic viewpoint of the predental student may be different from that of the general run of liberal arts students, even though we grant that it would be better for his professional career if he did not have this specialized viewpoint. Perhaps the junior college program sought by the liberal arts administrators will eventually provide a remedy for this condition. At any rate, closer cooperation between the dental educators and teachers of physics would react to their mutual advantage and to greater service to the general public health.

Inaccuracies in the Textbook Discussions of the Ordinary Gas Laws

W. James Lyons
Department of Physics, Loyola University, New Orleans, Lousiana

MANY physicists, and particularly teachers, must have been annoyed by the confusion that exists in the textbooks with regard to the generalization variously known as Gay-Lussac's or Charles' law. Recognition of the confusion as such, is more than pedantic quibbling when the confusion is contracted by students in a subject that prides itself on being the most exact of the inductive sciences. Students may learn the law from one textbook under one name, and find no mention of the other. They may study it later under the other name, without identifying the two statements. Still later, having finally concluded that the two statements are substantially the same, and that either name may be used for the law, it is possible for them to read that the names apply to different laws. The process might be reversed, or be made even more complicated.

A recent examination of numerous physics textbooks uncovers gross contradictions in the treatment of the discoveries of Charles and of Gay-Lussac. Most books, in describing the discovery and law (under one or the other name), agree in that they associate volume-increase with temperature-increase at constant pressure. For reasons of pedagogy or brevity, the texts may specifically mention the coefficient of expansion or absolute temperature in the statement of the law.

At least two discussions have been published, however, which do not confine the law to a relation between only volume and temperature. A textbook of fifteen years ago states that Charles, in 1787, was the first to measure, for different gases,

> "the ratio between the increase in pressure per degree and the value of the pressure at 0°C"

finding

> "that the pressure coefficients of expansion of all gases are the same. This is known as the law of Charles."

From this relation the more familiar volume-temperature statement is correctly differentiated, it being entitled "the law of Gay-Lussac," to whom the initial experimentation, in 1802, is ascribed.

In a recent textbook (1937) this distinction between the concepts embodied in the two rules is greatly minimized; both are given as Charles' law, "second form" and "first form," respectively. The name of Gay-Lussac appears once in the book, in a footnote. Another modern textbook credits Gay-Lussac with the volume-temperature law, without mentioning Charles.

A fourth book, in which the name of Gay-Lussac nowhere appears, states that "by careful experiments Charles found . . . that

$$V = V_0(1+t/273).$$"

But another, advanced work avers that he made "rather crude" experiments on air and carbon dioxide only. It might be remarked that the confusion and inaccuracy are not confined to introductory volumes; nor do the examples cited here exhaust the list.

Obviously, then, there is a demand, in the interests of historical accuracy, sound pedagogy, and uniformity, for a survey of the situation. An examination of the original memoirs brings out quite clearly the role played by each investigator in the establishment of the gas laws and, at the same time, uncovers some early, but significant contributions not generally recognized in modern books.

Critical Survey

The only record we have of Charles' researches pertaining to the ordinary gas laws is the two paragraphs given by Gay-Lussac in the report of his own classic experiments.[1] Gay-Lussac wrote, in part,

> "Before going further, I ought to remark that, although I had noted a large number of times that the gases oxygen, nitrogen, hydrogen and carbonic acid, and atmospheric air expanded equally between 0° and 80°, cit. Charles had noted, fifteen years ago, the same property in these gases; but not having published his results, it is by the greatest accident that I know of them."[2]

[1] J. L. Gay-Lussac, "Recherches sur la dilatation des gaz et des vapeurs. . . ," Annales de Chimie (1) **43**, 137 (1802).
[2] The 80° mentioned here is on the Réaumur scale; one

This statement suggests that Charles was familiar with the relation usually associated with his name; that is,

$$v = v_0(1+\alpha t), \qquad (1)$$

at constant pressure. Gay-Lussac's subsequent description of Charles' apparatus and tests indicates, however, that the latter endeavored to measure the increase of pressure of the gases when they were heated from the freezing point of water to its boiling point. But he neglected to keep the volumes of the gases even approximately

Joseph Louis Gay-Lussac (1778–1850)
(From Sneed's *General Inorganic Chemistry*, courtesy of Ginn and Company.)

constant, so that he cannot be said to have established or verified even the relation between pressure and temperature at constant volume. Evidently, what Charles actually measured was the combined effect of pressure- and volume-increase due to heating. Uniformity of behavior between the different gases would necessarily follow from the use of the same apparatus, and repetition of the initial conditions. Summarizing, Gay-Lussac said, "It appears to me, therefore, that one is unable to derive from these experiments the true expansion of gases."

While Charles, as early as 1783, was evidently familiar with the properties of gases used in balloons, and had probably noted an approximate uniformity of behavior between different gases, there is no evidence that he clearly recognized the possible existence of Eq. (1) as a universal law. Certainly the lack of refinement in his tests, and his failure to announce what findings he had made, are not characteristic of a man who detects the possible operation of a general principle of nature. Having given no description of his tests, nor supplied any experimental data as proof, he cannot be credited with having *established* either the volume-temperature or pressure-temperature relation. Certainly he did not furnish science with the first determination of either temperature coefficient. The conclusion he communicated to Gay-Lussac is little more than an opinion.

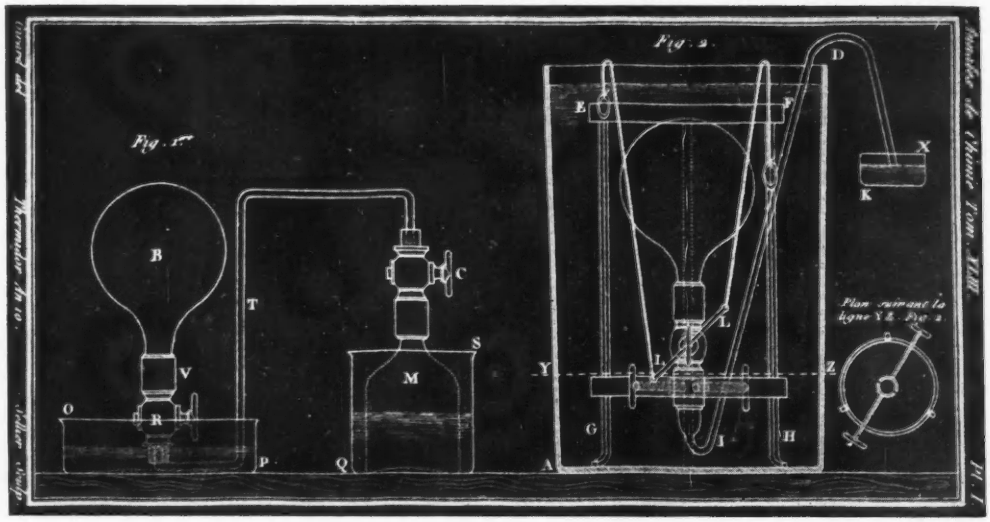
Dalton, it would appear, deserves more credit for Eq. (1) than does Charles. In 1802 Dalton reported[3] measurements of the coefficient of expansion in "a great many experiments made . . . on common air, and likewise upon hydrogenous gas, oxygenous and nitrous gases, and carbonic acid gas." He found the expansivities of the different gases to be substantially the same over the same temperature range. Speculating on his results, he anticipated Gay-Lussac with the statement,

> "Upon the whole therefore I see no sufficient reason why we may not conclude, that *all elastic fluids under the same pressure expand equally by heat*—and that *for any given expansion of mercury, the corresponding expansion of air is proportionally something less, the higher the temperature.*"

It should be pointed out that Charles, Dalton and Gay-Lussac did not initiate research on the thermal expansion of gases. As Gay-Lussac indicates in his exhaustive historical survey of the subject, the problem had occupied the attention of physicists, especially in France, all through the

recently-published physical chemistry textbook erroneously indicates 80°C.

[3] John Dalton, "On the Expansion of Elastic Fluids by Heat," Memoirs of the Manchester Literary Society **5**, part 2, 595 (1802).



FIGS. 1 AND 2. Plate from Gay-Lussac's paper (Reference 1), showing his apparatus. Fig. 1 is the arrangement for filling bulb *B* with various gases. Fig. 2 shows the bulb in the water bath for expansion measurements.

eighteenth century.[4] Various of the available gases were tested and their behaviors compared, coefficients of expansions were computed, and the results were published and criticized. A Colonel Roy, for instance, found for air a coefficient of 1/272 on the Réaumur scale, while Saussure fixed it at 1/235. Priestley made tests on ten different gases, including air. The results of these experiments were discordant, however, and each was found, subsequently, to be deficient in some important respect. Nevertheless, almost any one of these experimenters contributed more toward the definition of the problem than did Charles.

Gay-Lussac took the step of announcing the volume-temperature relation in its *correct* form [Eq. (1)] as a *general* law, *experimentally* established. Precise definition, generality, and an experimental basis being important criterions for a physical law, we conclude that only Gay-Lussac's generalization can be regarded as such a law. His technic, benefiting from the errors and inaccuracies in previous methods, was the most refined in its time (Figs. 1 and 2). In addition to the gases mentioned previously, Gay-Lussac made tests on hydrogen chloride, sulfur dioxide, "nitrous gas," and ammonia, all of which he found to "expand equally with the same degree of heat." He obtained for the coefficient of expansion the value 1/266.66. His research furnished a point of departure, and his law a reliable guide, for the more refined, subsequent experimentation of Regnault and others. Gay-Lussac's tests were quantitative, his results agreeing substantially with those of Dalton.[5] In comparison, the latter's conclusions suffer from vagueness, if not ambiguity.

Expressed symbolically in Eq. (1), the law of Gay-Lussac may be stated correctly for present-day application: *All ideal gases, at constant*

[4] Not included in Gay-Lussac's survey is the work of A. Volta on the expansion of gases, mentioned by J. W. Mellor, *Comprehensive Treatise on Inorganic and Theoretical Chemistry* (Longmans, London, 1922), I, 158–60.

[5] In this connection, attention is called to the following paragraph from Cajori's *History of Physics* (ed. of 1899), p. 198: "His [Dalton's] conclusions did not quite agree with Gay-Lussac's. The latter had shown that, using a mercury thermometer, the expansion per degree is a constant fraction of the volume at some arbitrarily fixed temperature. Dalton, on the other hand, claimed that the increment of volume for each equal rise of temperature is a constant fraction of the volume at the temperature immediately preceding. The question was decided by Dulong and Petit in favor of Gay-Lussac." Cf. also Mellor, reference 4. Examination of Dalton's original memoir leads one to question this interpretation of his conclusions. In comparing the expansions over the two intermediate ranges of temperature between 55° and 212°F, it appears that he expresses *both* as fractions of the volume at 55°. He repeatedly observed that these fractions were not constant, but slowly diminished as the temperature range was raised.

pressure, expand in the same proportion of their volumes with the same increase in temperature. The proportion for each degree centigrade rise in temperature, the coefficient of expansion, is 1/273 of the volume at 0° centigrade. The simpler modification involving absolute temperature introduces a concept which, in Gay-Lussac's time, was in the embryonic stage. The statement in this latter form should be designated as a modification. On the other hand, the statement of the dependence of pressure on temperature at constant volume, namely

$$p = p_0(1+\beta t), \qquad (2)$$

cannot properly be called Gay-Lussac's law, nor a form of it. Eqs. (1) and (2) do *not* "amount to the same thing."

Though Eq. (2) is a mathematical necessity of Boyle's and Gay-Lussac's laws combined, and from that point of view, cannot be strictly regarded as a distinct, empirical law, it was studied independently a hundred years before Gay-Lussac's work. Guillaume Amontons (1663–1705) in 1699 concluded[6] from measurements made on air thermometers, "that unequal masses of air increase equally in pressure with equal degrees of heat, and contrariwise." The fundamental significance of this conclusion must have been apparent to Amontons; he continued his work with air thermometers, and in a second memoir[7] improved the statements of his conclusions, as a result of the additional experimentation. The statement quoted above Amontons now submitted as an approximation. To this he added "that the greater the compression on masses of air, the greater is the increase in pressure for the same degree of heat." This appears to be Amontons' nearest approach to Eq. (2). Having no exact temperature scale, he could compute no coefficient; his lower temperature he refers to simply as "tempéré." Amontons' tests were confined to air, and involved pressure measurements at only the initial and final temperatures. His reports indicate no fine discrimination between volume and pressure increases. However, his researches and methods were models for their time; and they initiated the line of investigation that culminated in the work of Dalton and Gay-Lussac.

[6] G. Amontons, "Moyen de substituer commodement l'action du feu. . . ," Memoires de l'Academie Royale des Sciences, 112 (1699).

[7] G. Amontons, "Discours sur quelques propriétés de l'Air. . . ," Memoires de l'Academie Royale des Sciences 155 (1702). In a later memoir, "Le Thermometre. . . ," Memoires de l'Academie Royale des Sciences 50 (1703), Amontons introduces what may be the first speculations on the absolute zero of temperature.

Summary

Adopting the chronological order, we note briefly that,

(1) Amontons, during 1699 to 1702, experimented with various air thermometers, and in the latter year established in semi-quantitative form the law of change of *pressure* with temperature;

(2) Charles, before 1790, was very familiar with the properties of gases useful in balloons, but never published anything on the gas laws, and does not appear even to have known of any precise law involving temperature;

(3) Gay-Lussac, in 1802, was the first to publish an accurate statement of the law of the change of *volume* with temperature;

(4) Dalton, working about the same time as Gay-Lussac, published his results, but did not infer from his data the precise form of the law;

(5) Finally, Gay-Lussac's name, indubitably, should be associated with Eq. (1); and, if Eq. (2) is treated as an empirical law, Amontons' name may be appropriately associated with it (as suggested by Mellor).

It is not implied here that Charles and Dalton should be ignored in a discussion of the gas laws. Indeed, with the treatments in the literature being what they are, it is highly desirable that the student be made familiar with the name of Charles, for use in later reference. But even where the objective is to teach the law briefly and directly, without historical sidelights, there is no necessity for distorting the facts, as has been done.

The work of Charles and Dalton, though unknown to Gay-Lussac at the outset of his experimentation, may be treated as preliminary exploration, indicative of the trends of physicochemical thought at the time. Evidently, science had progressed to a state where research and analysis were converging on the law from several directions.

Reproductions of Prints, Drawings and Paintings of Interest in the History of Physics

E. C. Watson
California Institute of Technology, Pasadena, California

3. Caricatures of Early Steam Coaches

THE interest that developed in England about 1830 in steam vehicles is reflected in the many caricatures of steam cars which appeared at that time. Eight of these are reproduced here. While it appears to be human nature to ridicule new inventions, it will be seen that the new steam carriages fared rather well in these caricatures, which are on the whole truly humorous and often prophetic rather than merely truculent. Several of the coaches are, it is true, shown exploding violently, but actually boiler explosions were not infrequent, even if only one fatal accident is recorded.

In the early thirties steam coaches operated successfully as public carriers in London and on some of the main coach roads of England. Public sentiment against them was aroused, however, by the stage owners and drivers who feared that they would be robbed of business and by the farmers who anticipated the loss of a market for their horses. The "steamers" were ridiculed and even stoned and trenches were dug across the roads to impede their progress. In 1836 the English Parliament passed a law requiring that a steam coach should be preceded by a man on foot with a red flag to warn people on the road, and also permitting such heavy tolls on steam vehicles that operation at a profit became impossible. At the same time the steam railways with their higher speed were taking more and more of the passenger traffic and proving so profitable that business enterprise turned to their development. As a consequence, by 1836 the mechanical road carriage was practically abandoned in England; its further development has taken place mostly in America, France and Germany. (It is interesting to note that at present—almost exactly one hundred years later—because of the construction of excellent public highways the tables have been largely turned on the railroads.)

One of the caricatures here reproduced (Fig. 1) is by John Leech (1817–1864), best known for

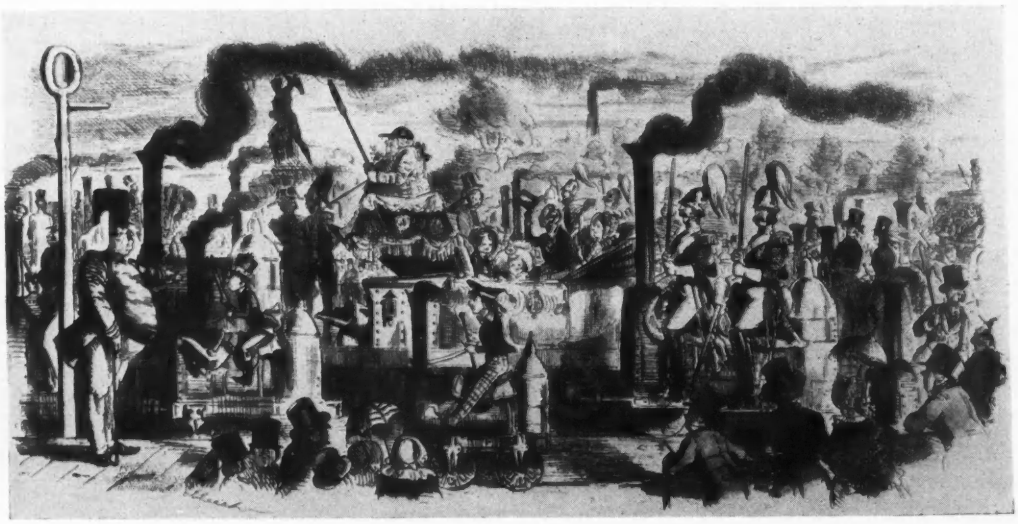


Fig. 1. "Hyde Park as it will be."

FIG. 2. "Walking, riding, and flying by steam."

FIG. 3. "By-and-bye a Man will go a hunting after breakfast upon his Tay-kettle."

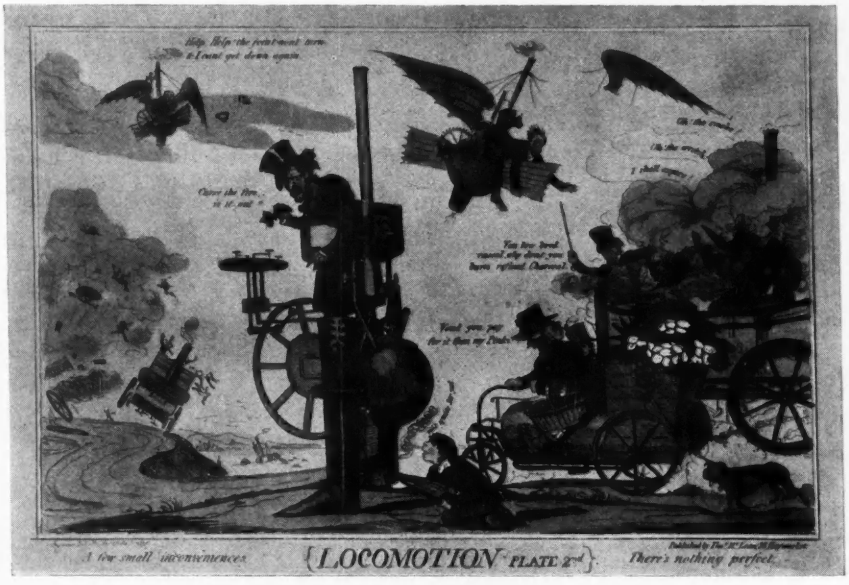


FIG. 4. "A few small inconveniences."

FIG. 5. "Going It By Steam."

FIG. 6. ". . . Fellow, give my Buggy a charge of Coke, . . ."

FIG. 7.

FIG. 8.

his woodcuts in *Punch;* another (Fig. 6) is one of a series of four, entitled "The Progress of Steam," executed by HENRY ALKEN (fl. 1816–1831), famous for his sporting prints; and a third (Fig. 4) is by ROBERT SEYMOUR (1800–1836), the first illustrator of *Pickwick* and the creator of the types of Pickwick, Winkle and Tupman on which no successor has contrived to improve. The artists who executed the rest are unknown as the signatures "Shortshanks," "Sharpshooter," etc., are obviously pseudonyms. The originals are all colored, are approximately 9 by 13 inches in size and were published by Thomas McLean, 20 Haymarket Street, G. Humphrey, 24 St. James Street, and G. King, Chancery Lane, all of London.

A Null Method for Measuring Electromotive Force with a Ballistic Galvanometer and Condensers

ARTHUR W. SMITH
Department of Physics, University of Michigan, Ann Arbor, Michigan

THE usual arrangement for measuring the electromotive force of a battery by the condenser method is to charge a condenser by applying the unknown emf and then measure the charge $Q(=CE)$ by discharging the condenser through a ballistic galvanometer. By repeating the operation with a known emf, the value of the unknown emf can be determined as precisely as the deflections of the galvanometer can be read (on a calibrated scale), but no more so. As one student wrote on an examination, "It requires a quick eye and an active brain to read a ballistic galvanometer;" at best, the first throw of the galvanometer cannot be read with great precision.

In the method here described the known and unknown emf's are used to charge two separate condensers. The condensers are then connected together, positive to negative; the electron charge in each flows into the other, and only the net resulting charge is passed through the galvanometer. When one of the capacitances is continuously variable, the charges can be made equal and the deflection zero. With charges which separately may be several times the amount that can be measured by a direct deflection of the galvanometer, a balance can be obtained to within 0.1 scale division; thus, the accuracy is many times greater than that of the direct deflection method.

The arrangement of the apparatus is shown in Fig. 1. When the double-pole, double-throw switch S is closed downwards, the points M and B are connected, allowing the condenser C_1 to be charged by the battery whose emf is E_1. At the same time N and A are connected by the other blade of the switch and C_2 is charged by E_2. When the switch is closed upwards the points A and B are connected through VW, and the condensers are joined to each other; the positive charge in one is neutralized by the negative charge in the other, leaving the difference, if any, divided between the two condensers in proportion to their capacitances. When the key K is closed this remaining charge passes through the galvanometer and gives a small deflection.

The key K must not be closed before the blades of the switch S have made contact at *both* V and W; otherwise one of the condensers will discharge through the galvanometer and a very large deflection will result. In order to protect the galvanometer, K must be made a part of S, or be connected to it, so that both blades of S will make their contacts a short time before K is closed. A three-bladed switch is useful for this purpose; two blades are used for S, and the contact clips for the third blade are cut short and used for K. The key K is necessary. It might seem that the two condensers could be discharged through the galvanometer at about the same time by closing the switch S very quickly; then the deflection would measure the difference between the charges. This might be true when the charges are small, but when they are 100 times the amount that would give a full scale deflection, as may be the case, even a massive moving coil will not remain at rest when equal and opposite discharges are passed through it in quick succession. If the scale is viewed through a telescope, the effect of the double discharge is to blot out the scale for an instant and then to have it reappear at about the original position; this occurs at the time one is trying to see whether the deflection is a few tenths of a division towards the left or the right. If the condensers are first discharged by the double-pole switch S, and then the balance of the charge allowed to pass through the galvanometer by closing K, the small deflection can be observed even when it is less than 0.1 mm.

By adjusting the capacitance C_2, the deflection can be made zero. Then, since the charges are equal, $C_1E_1=C_2E_2$ and

$$E_1=E_2C_2/C_1. \tag{1}$$

Thus the value of E_1 is directly proportional to C_2, which should be the adjustable capacitance.

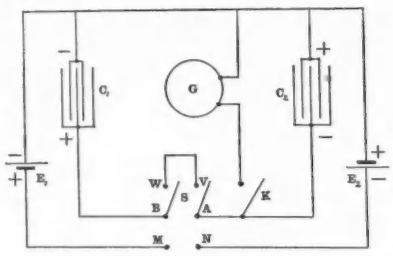


FIG. 1. Diagram of apparatus.

If the smallest step in C_2 is too large to give an exact balance, the correct value can be determined by interpolation between the deflections obtained from the nearest values of C_2 on either side of the value that would give the balance.

The accuracy of the method is further increased by comparing E_1, not with E_2 as in Eq. (1), but with another emf E_1' that is used in the same position as E_1 for a second balance. Then, when C_2 has been adjusted for a balance with E_1', Eq. (1) becomes

$$E_1' = E_2 C_2'/C_1. \tag{2}$$

Division of Eq. (1) by Eq. (2) gives

$$E_1 = E_1' C_2/C_2'. \tag{3}$$

Eq. (3) shows why the actual values of E_2 and C_1 need not be known. They do not enter into the computation for E_1, but they must remain constant while the measurements are being made. Precautions must also be taken to avoid the effects of leakage and residual charge.

When E_1 is nearly equal to E_1', it can be measured more accurately than the value of C_2 is known. This can be shown by writing

$$C_2 = C + c \quad \text{and} \quad C_2' = C + c', \tag{4}$$

where C is the capacitance of those sections of the condenser that are used in both C_2 and C_2', and c, c' are the parts of the capacitance that are changed in making the balances. Then Eq. (3) becomes

$$E_1 = E_1'(C+c)/(C+c') = E_1' + E_1'(c-c')/(C+c'), \tag{5}$$

where the second term in the last member is the only part of E_1 that is subject to experimental error. If C is undisturbed, an error in the determination of the change from C_2 to C_2' will introduce only a very small error in the measured value of E_1. In one case, when comparing two cells, the dial readings for C_2 and C_2' were 1.0679 and 1.0683μf, and the galvanometer showed a deflection for a variation of 1 in the last figure. Of course, the actual capacitance of C_2 was not known to five figures, but the 1.06 was the *same part* of the condenser in each case; and it makes little difference in the ratio whether the first three figures are 1.06 or 1.07.

Another advantage of this method is that a very high resistance in series with the unknown emf is no detriment; 10^6 ohms in series with E_1 make practically no difference in the setting of C_2, provided enough time is allowed for the condensers to charge. No measurement would be possible with a voltmeter or a potentiometer in such a case.

In making ordinary measurements this null method eliminates the need of using a carefully calibrated galvanometer scale.

Harry Arnold Baker, 1872–1937

PROFESSOR Harry Arnold Baker was born in Pittsburgh, Pennsylvania, January 20, 1872. He received the degree of Bachelor of Philosophy from Oscaloosa College, the degree of Master of Science from Trinity University, and a degree in chemical engineering from Reynolds College. He taught science and mathematics in Reynolds College, in Midland College, and in Wichita Falls and Vernon (Texas) High Schools until 1917, when he raised a company of volunteers at the entrance of the United States into the World War. From 1918 to 1920 he was an instructor in the Chemical Warfare Service, with the rank of captain. In 1921 he went to John Tarleton Agricultural College, Stephenville, Texas, as associate professor of chemistry. From 1923 until the time of his death he was professor of physics and head of the department. Professor Baker was a charter member of the American Association of Physics Teachers, and a fellow of the American Association for the Advancement of Science and of the Texas Academy of Science.

Acoustic Experiments on Fresnel Diffraction

HAROLD K. SCHILLING
Department of Physics, Union College, Lincoln, Nebraska

RECENTLY there was published an outline[1] of experiments in phonoptics[2] which have been performed in the writer's laboratory. The present article discusses some of those experiments which have not yet been described in detail; namely, those in the field of Fresnel diffraction.[3]

The main features of the apparatus have been described.[1] Fig. 1 illustrates the particular arrangement for the present experiments. Source S is in box B. The microphone M is mounted (Fig. 1b) so it can be moved circularly in a horizontal plane (Fig. 1a) about pivot P below the center of the aperture. For quantitative experiments, both the rod R and the supporting table are covered with sound absorbing material to eliminate reflection and consequent distortion of the field. The distance PM is usually 75 to 100 cm.

Rectangular real aperture (transmission)

Let the wave-length λ be 2 cm, and the slit width w, 1 cm. It is assumed that the student has already learned Huygens' principle. He will recognize therefore that the slit, having a width less than the wave-length, is a "line source" and thus should have no intensity maximums or minimums (no fringes) in its diffraction pattern. This is illustrated by curve a, Fig. 2, where the displacement of the oscillograph beam is plotted against the azimuth angle θ. Since the slit-to-microphone distance remains constant, the variation of intensity is due entirely to the obliquity factor.

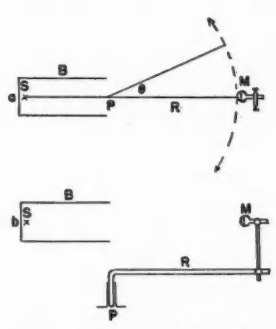


FIG. 1. Apparatus: a, plan; b, elevation.

Curve b, Fig. 2, depicts the pattern when both w and λ are 2 cm. This and subsequent curves differ from a in two important respects: first, there is an increase of amplitude and intensity, for $\theta=0°$, as might be expected for a wider slit; second, there are minimums and maximums.

The further evolution of the diffraction pattern[4] for slit widths of 3, 4, 6, 8, and 12 cm is shown by curves[5] c to h, Fig. 2.

According to Fresnel theory, the first minimum of intensity is due to the destructive interference[6] of waves coming from two half-period zones whose distances from the microphone differ by $\lambda/2$. Consistent with this prediction, direct measurement shows that the microphone at this minimum is one wave-length farther from one edge of the slit than from the other. Then, by covering successively each half[7] of the slit, it can be observed that energy is received from each zone separately. The fact that together they produce reduced intensity demonstrates destructive interference.

The first maximum is at a point whose distances from the edges of the slit differ by $3\lambda/2$. Here the slit can experimentally be shown to

[1] H. K. Schilling, "Acoustic Experiments in the Teaching of Optics," Am. Phys. Teacher **6**, 156 (1938).

[2] The development of such experiments with modern equipment in various laboratories has opened up a new field in the teaching of physics, to which it may in time be desirable to give a name. The term *phonoptics* is proposed.

[3] For discussions of Fresnel diffraction patterns in optics see for example, C. F. Meyer, *Diffraction of Light, X-Rays and Material Particles* (Univ. of Chicago Press, 1934), Chap. 4; Jenkins and White, *Fundamentals of Physical Optics* (McGraw-Hill, 1937), Chap. 8.

[4] For similar curves depicting optical diffraction see reference 3.

[5] For this series of curves a box $20\times20\times80$ cm was used. The cotton lining reduces the effective opening width to 15 cm.

[6] Since this is Fresnel diffraction these minimums will not in general have zero intensities.

[7] In Fresnel diffraction neighboring rectangular zones are not in general equal in area. However, when the receiver is at a great distance from the slits the areas of the zones approach equality; i.e., Fresnel type patterns fuse into Fraunhofer patterns. Errors introduced by considering the zones equal in width are not significant in these experiments.

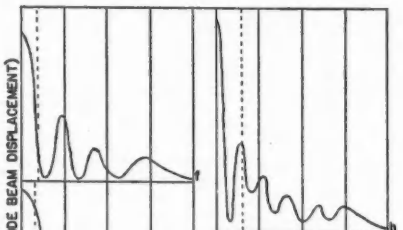


FIG. 2. Curves showing amplitude distribution in diffraction patterns of rectangular apertures of different widths. The dotted vertical lines indicate the edges of the geometrical beams, $a : w=1$ cm, $b : w=2$ cm, $c : w=3$ cm, $d : w=4$ cm, $e : w=6$ cm, $f : w=8$ cm, $g : w=10$ cm, $h : w=12$ cm.

contain three zones as predicted by theory. If approximately one-third of the slit is covered—that is, the zone at the edge—the maximum is seen to become a minimum. This is due, of course, to the destructive interference of the waves from the remaining two zones whose distances from the microphone differ by $\lambda/2$. If two-thirds of the slit are covered, one again obtains a maximum, with an intensity nearly equal to that obtained from the whole slit. Finally, if the middle zone only is covered, the two zones remaining open are at such distances from the microphone that the interference is constructive. The intensity is greater than when the whole slit is open.

Higher orders of fringes may be analyzed in like manner.

Figure 2 shows definitely that: as w increases (1) the deviation of the first "dark fringe" decreases; (2) the energy concentrated within the geometrical beam increases; (3) the number of fringes increases; (4) the largest number of minimums possible for a given slit width is w/λ. Such experiments give the student a feeling of familiarity with fundamental concepts that can be achieved in no other way known to the writer. Furthermore, a sequence of curves like those of Fig. 2 greatly aids the instructor in making clear the meaning of "rectilinear propagation," the conditions permitting the production of a narrow beam, the relation between undulatory and geometrical optics, and the question as to when it is legitimate to use either the wave-front method or the ray method of solving a problem.

Rectangular virtual aperture (reflection)

For the experimental arrangement see Fig. 3. The arm R carrying the microphone M is pivoted at p below a rectangular reflector. The sound then seems to come from virtual image S' and to pass through a virtual aperture at r. This is so oriented that the center c of the reflected beam, from which the azimuth angle is measured, is just outside the direct beam from the source S. The microphone therefore receives only reflected sound in all positions $0° < \theta < 90°$.

Curves may be obtained similar to those for transmission.[8] Also, the procedure in experimentally analyzing the conditions for interference, and isolating individual zones and their effects, is essentially the same. Unfortunately, the effect of a given zone can obviously not be eliminated simply by covering part of the slit.

FIG. 3. Schematic plan drawing of apparatus for reflection experiments.

Instead, one must somehow either make the desired zones nonreflecting or remove them altogether. The latter alternative is less difficult.

To analyze a given curve, say for w equal to 8 cm, the writer uses a set of divided reflectors whose over-all widths are equal. He has one reflector 8 cm wide; a pair of reflectors each 4 cm wide, which when mounted contiguously in the same plane constitute together an 8-cm reflector;

[8] To conserve space such curves are not shown.

an equivalent set of three reflectors each 2.66 cm wide; four reflectors each 2 cm wide, etc. These may be supported on a block with two narrow grooves (Fig. 4), which in turn is supported on an optical bench, or otherwise, by means of a rod *R*. To study the first minimum the arrangement of Fig. 4a is used first. After this pair of reflectors has been shown, just as a matter of check, to yield the same curve as does the equivalent single reflector, the microphone is set at the point where, presumably, there is destructive interference of the sound from the two halves. Then, if either zone is removed, the other is observed to send energy to the microphone. Thus we have the same sort of experimental proof of actual interference as was had in the case of transmission. To clinch further the point, one can then move one zone to the other groove one-

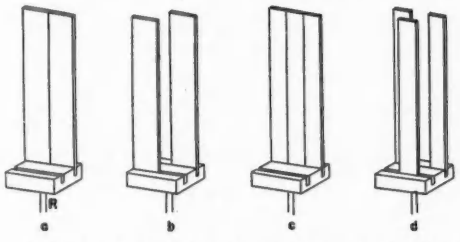


FIG. 4. Device for isolating effects of individual reflecting zones.

half wave-length removed from the first (Fig. 4b). The waves reflected by one zone therefore travel one wave-length farther and arrive at the receiver in phase with those from the other zone, thus yielding constructive interference.

To study the neighboring intensity maximum, one begins with the arrangement of Fig. 4c. Removal of the first strip decreases the intensity since the other two interfere destructively. Removal also of the second increases it again, only one zone still being operative. Replacing zone 1, but not zone 2, doubles the amplitude by constructive interference so that one has greater intensity than when all three zones or only one are operative. Now if zone 2 is placed in the second groove (Fig. 4d), the waves from all three[9] will be in phase and still greater inten-

[9] The critical reader will notice that, in the arrangement of Fig. 4d, one zone casts a "shadow" on another. Since the angle of incidence is small, however, this will not seriously affect the results.

It should be recognized that this arrangement also illustrates the principle of the familiar phase reversal zone plate.

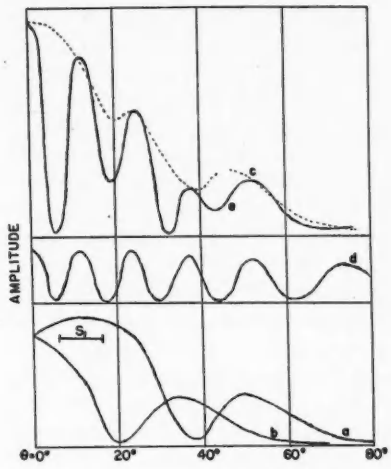


FIG. 5. Curves showing amplitude distribution in diffraction pattern of double slit system.

sity results. Other permutations of zones can also be studied with profit, as can higher order fringes.

It will be observed that, because of the possibility of demonstrating phase reversal, reflection yields even richer results than transmission. Curiously, however, diffraction by reflection is discussed only rarely in books on optics, except for the case of reflecting gratings. These experiments naturally lead to the consideration of important problems such as that of the range of applicability of the law of reflection and the question of the legitimacy of the ordinary method of deriving it by Huygens' principle without mention of interference; or of the role played by the size of the reflector, etc.

Double slit

Four variables determine this diffraction pattern: wave-length, slit width, slit separation, and the distance from the slits to the receiver. For a thorough understanding of diffraction, the student should be able to isolate the function of each variable both theoretically and *experimentally*. Though the theory is well known, there has heretofore been no pedagogically satisfactory method of experimental verification.

Figure 5 illustrates the method of analysis

when λ is 2 cm, w, 4 cm, the separation s between slit centers, 10 cm, and the distance d from microphone to center of slit system, 50 cm. Curves a and b give the diffraction patterns of the individual slits, one slit being covered while the curve is obtained for the other. They are alike, though displaced horizontally with respect to each other. Line segment s indicates the limits of the geometrical beam determined by one slit. Curve c is obtained by adding the ordinates of curves a and b; it may be thought of as determining the availability of energy in the field of radiation. Curve d shows the experimentally determined amplitude distribution in the system of interference fringes due to two very narrow slits ($w<\lambda/2$), whose separation s ($=10$ cm) is the same as that of the wider slits. According to theory the interference fringes of curve d should be superposed on the diffraction curve c. That this is actually the case is shown by curve e, which was obtained when both of the wider slits were open and therefore shows the effects simultaneously of diffraction and interference.

Similar analyses can be made for other values of the variables. To isolate the effect of one variable, all others are kept fixed while it passes through a series of appropriate values. Since the purpose here is merely to illustrate experimental possibilities, no theoretical generalizations are made regarding the role of each variable and no other curves are shown.

Reflection yields the same type of results.

Multiple slits

One can obtain curves for transmission and reflection gratings and study the function of each variable previously enumerated as well as of a fifth, namely, the number of slits.

Circular aperture

For these experiments to be successful a larger box should be used. Its width and height should be *at least* ten times the diameter of the microphone. The length should be correspondingly longer to yield approximately plane waves.

As predicted by theory, maximums and minimums appear along the line through the source and the center of the aperture; maximums at points for which the aperture includes an odd number of half period zones as demonstrated by direct measurement, and minimums where an even number are subtended. As in the case of rectangular apertures, the effects of individual zones or combinations of zones can be isolated and analyzed by covering appropriate parts of the aperture.

The diffraction pattern off the axis is also worth investigating. It will assume special importance in the next section.

Circular reflectors may again be thought of as virtual apertures. The same analyses can be carried through, by the method of divided reflectors.

Circular plane reflectors are selective with respect to wave-length.[10] How this characteristic can be studied with this equipment will be recognized by every teacher.

Curved reflectors

Much misunderstanding exists among students about the nature of foci or of images of point sources. They have difficulty in getting beyond the conceptions of geometrical optics according to which parabolic mirrors, for example, focus light upon points rather than focal spots, as required by diffraction theory.

Here again the experimental approach of phonoptics is exceedingly fruitful. Building upon the considerations of the last section, the student soon realizes that "focus" necessarily means a *volume* of phase agreement and that "images" of point sources must be circular diffraction patterns. For a given mirror one can demonstrate the relationship between wave-length and focal cross-sectional area. Then, for a given wave-length, the relation between area of reflector and focal area can be studied. The writer uses a set of mirrors with equal radii of curvature but of different areas. Thus the student has the illuminating experience of discovering that a small mirror 5 cm in diameter, which in the optics laboratory yielded fine images, has no focus whatever for acoustic waves of wave-length 10 cm. For 2-cm waves there is a simple circular fringe system but certainly no "focusing" in the ordinary sense. He then successively uses

[10] See Stewart and Lindsay, *Acoustics* (Van Nostrand, 1930), p. 6. For discussions of related subjects from the viewpoint of acoustics see also: Jones, *Sound* (Van Nostrand, 1937), p. 100; Watson, *Sound* (Wiley, 1935), Chap. 9.

larger mirrors with consequent reduction in the size of diffraction patterns, until the focal area becomes smaller than the mirror and, finally, has a diameter of the order of a wave-length. This is of great practical importance in acoustics.[11]

Shadow effects

In the lecture room one of the most fruitful and interesting demonstrations is that of the Arago "bright spot" behind circular or spherical diffracting bodies. Even though the student may have been prepared for it by other experiments and by theoretical considerations, he is fascinated anew by the paradoxical fact that near the edge of the shadow there is less sound than at the center. For a wave-length of 2 cm a circular disk 20 to 30 cm in diameter does very well. Great care must be taken to align the apparatus properly. An optical bench greatly facilitates such adjustment.

The study of fringes behind rectangular obstacles is also valuable and interesting.

As suggested in the outline previously published,[1] many other significant experiments can be performed in this field of diffraction. It is not thought necessary to describe them in detail since the present discussion will probably suffice to acquaint the reader with appropriate technics and the kind of results that may be expected.

The data and curves (Figs. 2 and 5) were obtained by the writer's assistant, Mr. Arthur Raff. Grateful acknowledgment is made for this and other help he has given during the preparation of this paper.

[11] Stewart and Lindsay, Reference 10, pp. 5–6.

A Modified Form of Phonodeik

J. Edmond Shrader
Department of Physics, Drexel Institute of Technology, Philadelphia, Pennsylvania

THE phonodeik devised by D. C. Miller[1] is very convenient for demonstrating the characteristics of sound waves but must be constructed by a skilled mechanician if it is to operate successfully. Attempts to make a demonstration phonodeik were unsuccessful because friction in the mounting of the spindle could not be reduced sufficiently. This led to the development of a modified phonodeik which required less skill for its construction.[2] It has two parts: (1) the phonodeik unit, consisting of a diaphragm,

[1] *Science of Musical Sounds* (Macmillan, 1922), p. 79.

[2] A demonstration phonodeik is also described by G. G. Kretschmar, Am. Phys. Teacher 4, 90 (1936).

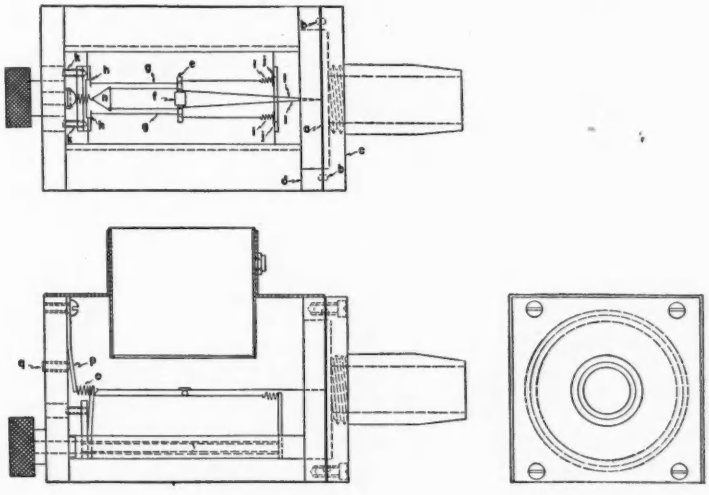


Fig. 1. Diagram of phonodeik unit (double scale).

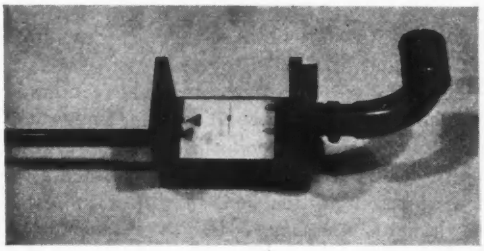


FIG. 2. Photograph of phonodeik unit.

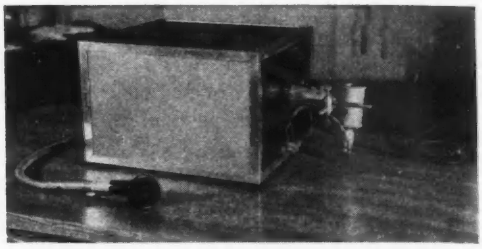


FIG. 4. Photograph of assembly.

its mounting, a spindle, and a mirror; (2) an assembly, in which the phonodeik unit is incorporated and which includes a source of illumination, a rotating mirror, and a ground glass screen. The phonodeik unit may be used satisfactorily with any suitable light source, a separately mounted rotating mirror, and a wall screen, but in the assembled form it is self-contained and ready to be plugged into an electric outlet.

The phonodeik unit is shown in Figs. 1 and 2. The diaphragm, of thin cover glass about 0.005 in. thick and 1.5 in. in diameter, is mounted between two soft rubber gaskets *b*,*b* and clamped between the metal parts *c* and *d*. The thin rod *e*, a piece of fine cambric needle, serves as a spindle and carries the mirror *f*. This spindle is supported by two fine tungsten wires *g*,*g* about 0.0005 in. in diameter. These wires are attached to the supports *h*,*h*, passed twice about the ends of the spindle, and then fastened to the light springs *i*,*i* carried by the flexible supports *j*,*j* so that the tension may be adjusted by the screws *k*,*k*. A loop of wire *l*,*l*, the same kind as that used to support the spindle, is attached to the diaphragm at its central part by a bit of cement, then is wrapped several times about the spindle in a direction opposite to that of the supporting

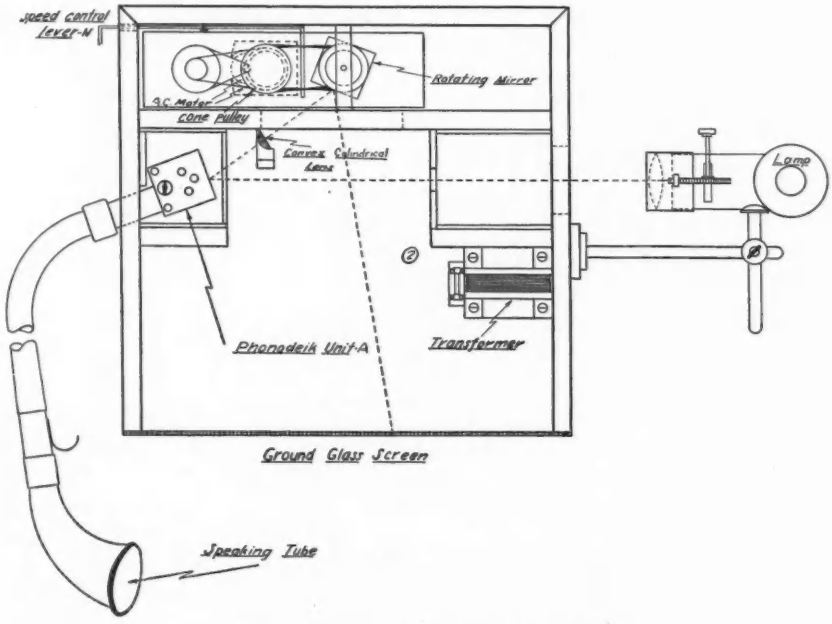


FIG. 3. Diagram of assembly (half-scale).

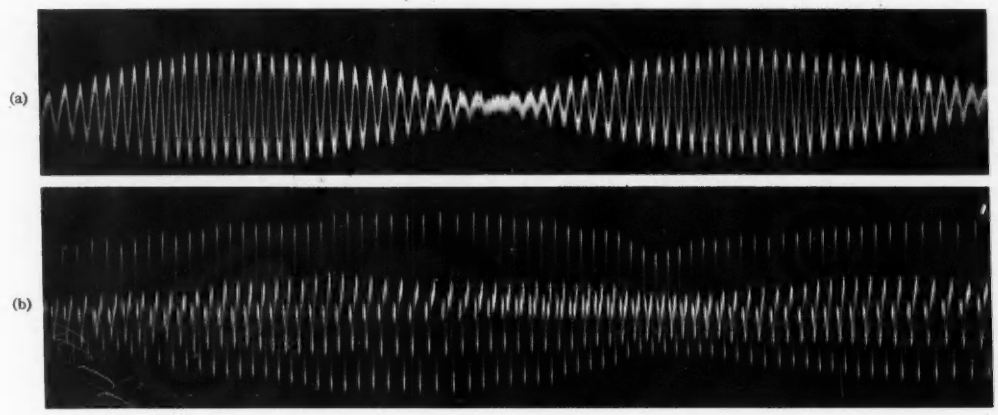


FIG. 5. (a) Beats due to two tuning forks of frequency about 250 vib/sec. (b) Trombone with vibrato.

wires, the ends of the loops passing about the spindle on either side of the mirror *f* and from thence to the light triangular piece of aluminum *n*, which is attached to the spring *o* carried by the support *p*. The screw *q* serves to adjust the tension on the spring and its attached wires. The spindle supported in this manner is caused to roll on its supporting wires when the diaphragm is actuated and a light beam falling upon the mirror may be deflected upon a rotating mirror and from thence to the screen.

Small tungsten wires were used as the supporting parts in the phonodeik unit because of the greater tension which may be employed to secure higher frequency-response to vibration. Fine silk thread or silk fibers also give good results, however, and are easier to manipulate in construction.

The complete self-contained apparatus is shown in Figs. 3 and 4. The box is about 15 in. square and 12 in. high, and one side consists of a ground glass screen. The phonodeik unit *A* is located on one side with the supporting wires in a vertical position so that the direction of deflection of the beam of light is vertical. A lamp having a concentrated filament and operated by a transformer is attached to the box on the side opposite the phonodeik unit. The lamp is fitted with a lens of about 6 in. focal length. The rotating mirror is operated by a small motor with reduction pulleys. The speed of the rotating mirror is further regulated by a pair of cone pulleys, the belt being slid up or down by means of the lever *N*.

The apparatus here described has been used mainly for visual observation and no attempts have been made to find the limits of its frequency response. To show high frequency traces, a small light source approximating a point source should be used. In the model constructed the traces tend to show that response is secured for frequencies possibly as high as 3000 vib/sec. Double amplitudes covering the range of the scale, about 10 in., have been shown.

The phonodeik unit was used in conjunction with a temporary set-up to secure photographs of certain characteristic vibrations. An arc lamp with restricted aperture was used as a light source. A 70-mm film, carried in a film holder and sprocket driven by a flexible drive attached to a motor, was carried past the slit at a speed of 3 to 4 ft/sec. While no great pains were taken in securing these records, Fig. 5 gives some idea of the results that can be obtained with the apparatus.

Reprints of Survey Articles for Class Use

Reprints of "A Survey of Piezoelectricity," by Walter G. Cady, may be obtained from the Editor. The cost of 6 reprints is 60 cts. postpaid.

Circuit Details for a Small Supersonic Oscillator of the Piezoelectric Type

WALTER C. BOSCH AND WALTER G. ALLÉE, JR.
Department of Physics, Tulane University, New Orleans, Louisiana

WITH increasing interest in the phenomena of supersonics, our laboratory required a supersonic oscillator for demonstration and experimental work. The general specifications for the oscillator were that it should be of a reasonably compact piezoelectric type, operating effectively with a power input of 200 to 400 w. The piezoelectric, rather than magnetostrictive, type was selected because it is especially useful in the study of the effects of supersonic vibrations on chemical reactions and biological specimens. It consists, briefly, of a driving vacuum tube oscillator tuned to resonance with, and providing a high voltage across, a quartz crystal immersed in a suitable liquid.

In a source paper, R. W. Wood and A. L. Loomis[1] have described a piezoelectric oscillator which requires equipment handling power in the kilowatt range. A recent paper[2] indicates that the Wood and Loomis circuit may be used at lower power levels, but no circuit details are given. The circuit described herein is a modification of the Wood and Loomis circuit built around 250-w tubes. It operates at a frequency of 220 kc/sec.

In the assembly of this circuit, the major item of expense is the X-cut quartz crystal.[3] With the exception of the inductance coils, the vacuum tube oscillator can be built of parts from the storeroom of the electronics laboratory. The special inductance coils and crystal electrodes can be constructed in the department shop. In our circuit, some of the meters and parts were salvaged from a dismantled long-wave transmitter. At the time the equipment was assembled, two Amperex HF200 tubes were the only 250-w tubes not in use in the laboratory. Designed for 6-meter circuits, these tubes performed so effectively at 220 kc/sec that they were retained in the final assembly.

The circuit used is a self-rectifying parallel feed Hartley oscillator and differs from that of Wood and Loomis in two ways: (a) a separate pair of grid excitation coils is not used; (b) the biasing arrangement serves for both tubes. The circuit and apparatus are shown in Figs. 1 and 2. As indicated by the dashed line in Fig. 1, the equipment is assembled in two units.

Unit 1, the vacuum tube oscillator, is mounted in "breadboard" fashion on a 2×4-ft tempered Masonite base. To conserve space, the tuning condenser bank of the tank circuit is mounted on a small vertical panel. The tank circuit inductance P consists of 76 turns of No. 10 hard drawn copper wire wound on a diameter of 7.5 in. and spaced 0.125 in. apart. The coil form is made of four wooden rings evenly spaced and joined together with four symmetrically placed notched hard rubber strips. The wire is wound into the notches and the coil is mounted on legs attached to the wood rings on each end. The secondary coil S has 1776 turns of No. 32 d.c.c. copper wire close-wound on a hollow hard rubber cylinder of diameter 3.75 in. Placed concentrically inside the primary coil, it is supported by solid Pyrex rods. This coil assembly is mounted as far from the power transformer TR_2 as practicable. For protection of the experimenter, the transformer is boxed, screens are set in place around the whole unit, and a red bulb lights when the high voltage is switched in.

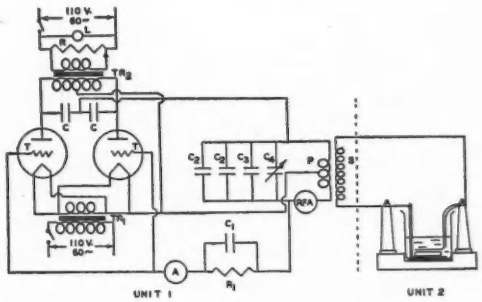


FIG. 1. Circuit diagram. L, red pilot lamp. R, input potentiometer. TR_1, filament transformer; 150 w, 110-v pri., 12-v sec. TR_2, plate transformer; Thordarson T6283 110-v pri., sec. 2350–0–2350 v, 250 ma. T, Amperex HF200. C, Dubilier mica; 2000 $\mu\mu$f, 6000 v. RFA, R.F. ammeter; 0 to 10 amp. C_1, Dubilier mica; 1200 $\mu\mu$f, 1000 v. C_2, Dubilier type-86 mica; 500 $\mu\mu$f, 12,500 v. C_3, Dubilier type-86 mica; 1000$\mu\mu$f, 12,500 v. C_4, variable air; 230 $\mu\mu$f, 6000 v. R_1, IRC fixed resistor; 150 w, 10,000 ohms. A, d.c. milliammeter; 0 to 150 ma.

[1] Phil. Mag. **4**, 417 (1927).
[2] W. Mayberry, Electronics **7** (July, 1937).
[3] Premier Crystal Laboratories, Inc., New York, N. Y.

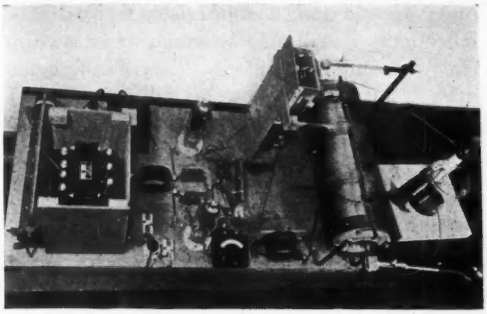


FIG. 2. Photograph of supersonic oscillator.

In unit 2, a 2-l Pyrex beaker, used as the container for the crystal and liquid, is fitted tightly into a circular opening in the 12×12-in. wooden base. A circular lead plate, of thickness 3/16 in. and diameter 4.75 in., is placed in the bottom of the beaker and serves as the lower electrode. The crystal, a flat cylinder of X-cut quartz with diameter 6.2 cm, thickness 1.3 cm, is placed on top of the lead plate. A thin brass disk, cut to the crystal diameter, is set on the crystal top as the upper electrode. A suitable amount of xylene or transformer oil is used to cover the crystal and electrodes. Connections to the electrodes are made through No. 10 copper leads fastened to 7-in. stand-off insulators. A short piece of light spring brass connects the rigid lead to the top electrode.

In setting the oscillator into operation, the connection between the units is broken. With the input voltage set at a medium value, the inductance and capacitance of the tank circuit are adjusted until a wavemeter indicates that the frequency of oscillation is nearly that of the crystal. The units are then reconnected and final adjustments are made. Vernier control is provided in the variable air condenser C_4. The accuracy of tuning is judged by the size of the mound raised on the liquid in which the quartz crystal is immersed. For best results, the depth of this liquid must also be carefully adjusted.

With transformer oil immersing the crystal, the oscillator described raises an oil mound 4 to 5 cm high at full power output. With this amount of supersonic energy available, it is possible to perform many experiments of the type described by Wood and Loomis[1] and others.

Galvanometer Resistance by Deflection

CHAS. WILLIAMSON
Department of Physics, Carnegie Institute of Technology, Pittsburgh, Pennsylvania

LABORATORY courses in electricity commonly include a determination of the current sensitivity of a galvanometer. A typical circuit for this purpose is shown in Fig. 1. In this case the resistance of the galvanometer must be known. Sometimes the student is told to consult the manufacturer's label or to ask the instructor for this constant. Often it is thought desirable for him to measure it. The Kelvin bridge[1] is standard for the purpose, but it ordinarily requires two additional resistances,[2] a complete rearrangement of the circuit, and an acquaintance with the theory of the Wheatstone bridge.

An alternative is the half-deflection method, which requires only one extra resistance-box, and no new theory. If we add a resistance c (Fig. 2) of such magnitude that the galvanometer deflection is halved, it is obvious that the galvanometer resistance G is approximately equal

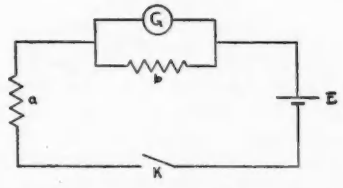


FIG. 1. Circuit used to obtain current sensitivity of galvanometer.

[1] Miller, *Laboratory Physics* (Ginn, 1903), p. 306; Starling, *Electricity and Magnetism* (Longmans, Green, 1920), p. 99.

[2] The diagrams given in the references in footnote 1 are merely schematic; the accompanying descriptions call for the use of an extra resistance or other means for reducing the galvanometer deflections. A complete diagram appears in Page and Adams, *Principles of Electricity* (Van Nostrand, 1932), p. 192.

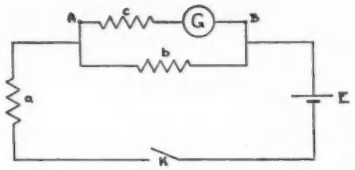


FIG. 2. Modification for measuring resistance of galvanometer.

to c, provided that b is small compared to G. This conclusion involves two important assumptions. The first is that V_{AB}, the potential difference between A and B (Fig. 2), is sensibly unchanged by the addition of c to the circuit. The second is that the deflections of the galvanometer are proportional to the currents in it.

Often neither assumption is justified. Let us take a numerical example in order to test the first one. Suppose that E is 1.50 v, a is 50,000 ohms, b is 10.0 ohms, and G is 100 ohms. If c is adjusted until the current in the galvanometer is half the original value, it may be shown by calculation that V_{AB} changes from 273 to 286μv, and that c is 110 ohms, differing from G by 10 percent. An algebraic solution shows that $G=c-ab/(a+b)$, which reduces to the approximation $G\doteq c-b$ when a is large, as in the present case.

The second assumption, that of proportionality in galvanometer deflections, can be checked only by a test. If errors are found, it is often possible to make two widely separated points agree by suitably bending the scale; but residual inaccuracies will then, in general, exist elsewhere.

A simple change in technic avoids both these sources of error. If, after halving the deflection by inserting the resistance c, we restore it to its former value by doubling b, the result will no longer depend upon a comparison of two different deflections; it will also be much more accurate. The procedure is as follows. The galvanometer is given a large deflection by adjusting b. This deflection is then approximately halved by inserting resistance at c. Next the value of b is doubled, and the deflection made exactly what it was at first by slightly readjusting c. A calculation based on the constants previously cited will show that V_{AB} is now almost exactly doubled while c is 99.96 ohms. Thus there is no appreciable error in taking c to be equal to the desired galvanometer resistance. An algebraic solution shows that $G=c(1+2b/a)$, which reduces to $G\doteq c$ when a is large, as in the present case. When this approximation is valid, the student need not be asked to obtain the complete algebraic solution; it is sufficient to point out that the changes in b and c do not appreciably alter the battery current, and that this is divided in the same ratio as before.

It will be noted that the task of matching two successive deflections of the same magnitude is easier than that of adjusting a second deflection until it is half the first. Moreover, a mechanical zero-error will not affect the result. If stray thermal emf's are noticeable, their effect may be minimized by reversing the polarity of E and averaging the observed values of c for the two trials.

Ordinarily the approximation $G\doteq c$ is more accurate than are the observations themselves. If the deflection is 25 ± 0.05 divisions, G is determined to 0.2 percent, a precision almost comparable to that of the resistance boxes in the circuit. For this accuracy c should read to 0.1 ohm.

Portfolio of Portraits of Eminent Physicists

AS has been announced in previous issues, plans have been made for a portfolio of portraits of twelve eminent non-living physicists, to be published by the journal, *Scripta Mathematica*, with the editorial assistance of a committee representing *The American Physics Teacher*. Since publication will not be undertaken unless there is evidence of some demand, readers who are interested in having the portfolio made available should send their orders immediately to *Scripta Mathematica*, Yeshiva College, New York City. The prepublication price is two dollars, payable on delivery.

The physicists whose portraits will be included are Newton, Galileo, Huygens, Ampère, Fresnel, Faraday, Joule, Clausius, Maxwell, Gibbs, Hertz, and Rowland. Each portrait will be approximately 25×36 cm, and will appear in a separate folder along with a biographical sketch written by Professor Henry Crew.

"A Minimum of Mathematics"

HENRY A. PERKINS
Department of Physics, Trinity College, Hartford, Connecticut

IT is a serious comment on our educational system that many college textbooks of elementary physics are advertised as containing "a minimum of mathematics." The assumption is that our students are unable to use even the very moderate amount of algebra, geometry, and trigonometry they are supposed to have acquired in school, and that a text almost innocent of mathematics will commend itself to the instructor.

If this assumption is correct, for what in the name of education is the teaching of mathematics good? After painfully learning how to solve quadratic equations, why must the student of elementary physics be protected from them as from a disease? If he has learned about sines and cosines and even reached the dizzy height of expanding $\sin(\alpha+\beta)$, why should he not be expected to project a velocity on the X-axis, or expand the sum of two angles when they have a physical meaning?

When a popular English physics text has to be simplified for American consumption, and when a Canadian author dares not include problems which Canadian students handle with ease in a text to be used in the United States, it is time for us to take account of our stock and to ask ourselves why we are so far behind our neighbors in the more rigorous branches of education. Probably we surpass the rest of the world in the teaching of civics, home economics and hygiene, all doubtless valuable subjects; but considering the manner in which they must be presented, they are child's play beside any exact science. Are we really a nation of children? Or, are we educators supinely catering to a supposed popular demand because, forsooth, we must entice an ever increasing number of students to our colleges in order to make both ends meet? This latter alternative would seem to be the true one. A young man at an important university told me that he was doing second-year physics. I asked him if any calculus was used, knowing that its elements were taught in the freshman year. "Oh, no," he said, "they wouldn't dare to use it, for if they did, no one would elect the course." Then why, in heaven's name, did they teach the calculus? What is mathematics for, if not to be used, unless, indeed, to entertain the pure mathematicians? It is on a par with a foreign language—no good if you cannot use it. And there also the results are equally discouraging. How many of a class after three painful years of French or German are able to read a scientific article in either language, converse with the natives of either country, or even read a French novel for pleasure?

The late Professor A. P. Wills of Columbia University, once told me that when he visited first-year physics classes in the Sorbonne, he was amazed to find the students handling without difficulty mathematics that he would not have dared to use with his first-year *graduate* students. But then the French go in for thoroughness, and no one goes to the universities unless he has some ability and is ambitious to learn.

However, in spite of our shortcomings, I still believe that it is a great mistake to cut down the mathematics in our elementary physics to a "minimum." It is not true that this makes a book easier, unless at the same time its content is greatly reduced. A simple analytic statement or proof is actually easier for the average student to grasp than a verbal explanation of the same thing in those cases where words may be substituted for symbols. What are symbols for, if not to simplify logical deductions? Not only are symbolic statements more concise, but also more easily understood, because many of our college students do not get much from what they read. Their mother tongue is like Greek to them when it deals with ideas and uses words not found in the pulp magazines. For instance, if the student reads that "moment of inertia is the sum of all the mass particles of which a body is composed, each multiplied by the square of its distance from the axis about which the body rotates," the chances are that he will not get the idea at all. But if we write $I=\Sigma mr^2$, having previously defined the various symbols, he will probably

understand it in spite of the dreadful Greek sigma. This is even more the case when an author gives verbal explanations of steps in a proof instead of expressing them algebraically. The result of such a policy is a text that appears much more innocuous than it really is, and whose verbal passages the instructor is constantly obliged to interpret in simple algebraic language.

One more most unfortunate form of pseudo-simplification in recent physics textbooks calls for a serious protest. I refer to the misleading practice of making a symbolic relation seem easier by assuming that one, or even two, of the quantities involved have unit value. A remarkable example of this appears in a recent publication where, in a conspicuous position, we find

$$\text{Work/Time} = \text{e.m.f.}$$

This looks as if e.m.f. were electric power, until the startled reader finds that the current value is supposed to be unity, which, of course, reduces the familiar equation $W = EIt$ to the form just given. Such a device is very bad pedagogy, to say the least, and it is certainly misleading.

Another example of this trend is the statement that the work of moving a unit magnetic pole against a field of strength H is given by $W = Hl$. This is true, of course, but it *looks* as if H were a force, because only the ghost of the pole strength m is present. How much better to write $W = Hml$ where there is no uncertainty and the dimensions on both sides are in agreement! Still another misleading statement is $F = m/\mu d^2 = H$ which also gives the impression that H is nothing but a force. The author, of course, explains that we are dealing with a unit pole, in which case F does equal H numerically, but the student almost unavoidably gets the impression that F and H represent identical concepts.

A final illustration is taken from a really excellent textbook on intermediate electricity. In calculating the coefficient of mutual induction of a standard solenoid with a secondary coil wound over its central portion, we find

$$M = n\phi = nHA = 4\pi NnA/L.$$

This looks simple, but is it? The suppression of I by setting it equal to unity is most unfortunate, and actually increases the difficulty. The statement should be as follows:

$$M = n\phi/I = nHA/I;$$

but $$H = 4\pi NI/L,$$

therefore $$M = 4\pi NnA/L.$$

The moral is that physics is inherently mathematical, and in teaching it, we are wronging our students if we deprive them of that training which is one of physics' greatest claims to prominence in a modern curriculum; namely, its call for the clear reasoning and accurate thinking that are demanded by an exact science.

Appointment Service

REPRESENTATIVES of departments or of institutions having vacancies are urged to write to the Editor, Columbia University, for additional information concerning the physicists whose announcements appear here or in previous issues. *The existence of a vacancy will not be divulged to anyone without the permission of the institution concerned.*

20. Ph.D. Univ. of Minnesota; S.B., S.M., M.I.T.; 1 yr grad. work, Univ. of Iowa. Age 38, married, 2 children. 17 yrs teaching experience in universities, colleges and technical schools, including 10 yrs head of department. Interested in progressive undergraduate and graduate teaching and research, including mathematical physics.

21. M.S. Kansas State. Age 38, married, 2 children. Research, acoustics. Experienced in laboratory maintenance, design and construction of apparatus, and writing of manuals. Desires teaching or industrial laboratory employment.

23. M.S., B.S. Louisiana State Univ. Age 24, unmarried. 2 yrs teaching fellow, physics; 2 yrs practical engineering experience; 2 summers, seismic prospectings. Desires teaching or industrial laboratory position.

24. Ph.D. Age 32, married, no children. Experience: 4 yrs secondary school; 4 yrs instructor, state university; 3 yrs head of physics and mathematics, liberal arts college. Author, laboratory manual. Two research grants. Desires position in larger college or university.

25. Ph.D. Yale. Age 33, married, 2 children. Industrial research experience; 3 yrs instructor in small college. Interested in teaching in coeducational or mens liberal arts college. Available June 1938.

26. Ph.D., with long experience in an American college in China, wishes a college teaching position.

27. Ph.D., physics, Northwestern '35; A.B., engineering, Harvard. Age 42, married, 3 children. Experience: 1 yr, lt., artillery; 12 yrs business and sales; 5 yrs college teaching. Interested in undergraduate teaching, including astronomy.

28. B.S. in E.E., M.S., physics, Dr. Phil. Nat. from German univ. (Exchange fellow from U. S.) Age 32. 7 yrs teaching experience in advanced courses and physics for engineers.

29. Ph.D., Northwestern; M.S., Pittsburgh; A.B., Muskingum. Age 34, married, 1 child. Has had 13 yrs teaching experience in two universities. Interested in teaching and research.

Departments having vacancies or industrial concerns needing the services of a physicist are invited to publish announcements of their wants; there is no charge for this service.

Any member of the American Association of Physics Teachers may register for this Appointment Service and have a "Position Wanted" announcement published without charge.

NOTES ON APPARATUS AND DEMONSTRATIONS

Adjustment of a Michelson Interferometer for Equal Light Paths

AMONG the manipulations of a Michelson interferometer that are often required of students, the most difficult is probably the adjustment for equal light paths, which is necessary in the search for white-light fringes. This note proposes a simple technic for making this adjustment.

The total number of colored fringes observable by white light is limited by the great spread of wave-lengths effective in the source. If, however, the white light is passed through a filter that transmits only a narrow band, the number of fringes increases to some larger value. It follows that these pseudo-monochromatic fringes are easier to locate than the white-light fringes. The latter lie at the center of the colored set, and can be found there after the filter has been removed.

Using the light of a tungsten lamp, filtered by a combination of the Corning monochromatic filters No. 4 (green) and No. 5 (yellow), I have observed about 200 fringes; this is about ten times the number seen with unfiltered white light.

WILLOUGHBY M. CADY

Department of Physics,
Cornell University,
Ithaca, New York.

A Visual Demonstration of a Measurement of the Speed of Sound in Air

STEDMAN'S method[1] of demonstrating visually a measurement of the speed of sound in air may be successfully applied to an open tube with sliding end section.[2]

In any electrical Kundt's tube method it is customary to analyze the effects produced at the source in terms of the small oscillating currents induced in the energizing circuit as a result of variations in the impedance of the latter, and brought about by changes in the acoustic reaction at the source. Computation of the wave-length of the sound vibrations is ultimately made, and hence the speed of sound is determined.

A modified technic is provided if we employ (a) a second telephone receiver purely as a sound detector, (b) an oscillating neon tube for energizing the source of sound instead of a valve oscillator, and (c) a method for automatic registration of the effects on a viewing screen, thus facilitating easy demonstration to an audience. This note pertains mainly to these modifications in describing a dual telephone method for measuring the speed of sound in air.[3]

The apparatus is shown in Fig. 1. The source of sound S is an electrically maintained telephone earpiece, energized by an oscillating neon tube and mounted at one end of a sliding pipe system. A second telephone receiver R occupies the other end of the pipe and functions as a detector of the aerial vibrations within the pipe. This receiver is connected either to a Westinghouse instrument rectifier and reflecting galvanometer in series for a frequency range 900–1000, or in the grid circuit of a two-valve amplifier outside this frequency range. The output of the amplifier is coupled to a circuit consisting of rectifier and shunted reflecting galvanometer.

When the distance between the source S and receiver R is equal to an integral number of half wave-lengths λ of the sound vibrations inside the pipe, stationary waves are formed. The diaphragm of the receiver responds to the pressure variations at that end of the pipe and, as the pipe length is gradually increased, the pressure effects upon the diaphragm change likewise. These pressure changes occur periodically with each successive half wave-length increase in pipe length, and the rectified currents passing through the galvanometer subsequently produce similar variations in the galvanometer response. The response curves for increasing pipe length exhibit marked maximums and minimums. The distance between successive peaks is equivalent to $\lambda/2$.

For visual demonstration to an audience, a light frame T_1 is rigidly attached to the sliding pipe. The frame carries a large sheet of graph paper and, by a suitable optical arrangement, a light spot is projected from the galvanometer mirror on to this paper. Conditions are made so that the spot moves at right angles to the direction of traverse, so that when the air column within the pipe is gradually increased, the spot of light in traveling across the paper

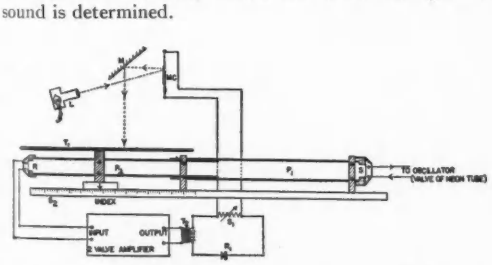


FIG. 1. Diagram of apparatus. P_1, P_2, fixed and sliding pipes; R_1, rectifier; T_2, transformer; S_1, variable galvanometer shunt; MC, moving coil of galvanometer; M, mirror; L, projection lamp; S_2, reference scale.

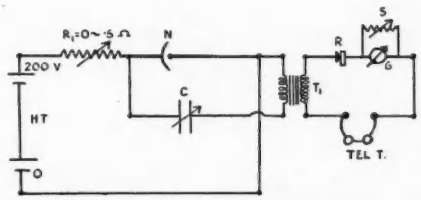


FIG. 2. Arrangement for open pipe. N, oscillating neon; C, variable capacitance; R, Weston Photronic cell or Westinghouse detector; T, telephone source; R_1, variable resistance.

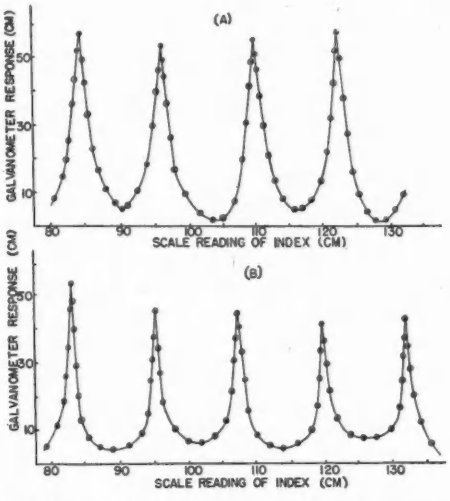


FIG. 3. Results for air. (a) Valve oscillator controlled source; $N = 1330$ vib/sec, $t = 18.5°C$. (b) Oscillating neon controlled source; $N = 1380$ vib/sec, $t = 17.5°C$.

automatically traces out a response curve. By marking the successive positions of the light spot for each pipe length, we automatically plot the galvanometer response curve from which the half wave-length is interpolated. The index and reference scale serves as an alternate means of measuring $\lambda/2$ when using a lamp and scale.

Measurement and control of the frequency of the source is performed stroboscopically. Since the oscillating neon tube operates at the same frequency as the source of sound, the intermittent light from the former is made to illuminate a stroboscopic disk mounted on the spindle of a synchronous motor driven from the a.c. lighting supply. Suitable selection of the number of triangles per ring on the disk enables the oscillating neon tube to be kept steady at any required frequency and fine control is effected by means of variable condenser tuning.

In view of the reduction in output of the oscillating neon tube with increase in frequency, it is advantageous to operate the telephone source at a sub-multiple frequency ($N/2$, $N/3$, etc.) of its natural frequency N. By this means more acoustical energy is available for sounding the pipe; hence the galvanometer response is larger. The response curves will exhibit the usual maximums and minimums, but with separation distance between the peaks corresponding to the natural frequency of the telephone diaphragm. In the dual telephone method, pre-selection of the source must be $N/2$, $N/3$, etc., where N is now the natural frequency of the receiver diaphragm.

In the case of the open sliding pipe we must resort to measurement at the source and the normal oscillating neon circuit needs modifying. Fig. 2 shows such an arrangement, the telephone source, rectifier and galvanometer being all in series in a circuit transformer coupled to the energizing circuit.

There is usually with this arrangement a sudden change in pitch when the resonant pipe length is reached and this provides one with a sensitive aural method of detecting accurately the position of the sliding pipe at resonance.

TABLE I. *Typical data; v_t, speed of sound in air at $t°C$; v_0, speed at $0°C$.*

FIG.	NO. OF PEAK	READING (cm)	λ (cm)	λ MEAN (cm)	TEMP. (°C)	N (vib/sec)	v_t (m/sec)	v_0 (m/sec)
3a	1	84.30	(3)−(1)					
	2	96.50	=25.70					
	3	110.00	(4)−(2)	35.75	18.5	1330	342.6	331.5
	4	122.30	=25.80					
3b	1	83.00	(3)−(1)					
	2	95.00	=24.50					
	3	107.5	(4)−(2)	24.60	17.5	1380	339.0	328.7
	4	120.00	=24.60					
	5	132.20	(5)−(3)					
			=24.70					

Typical response curves (reduced) for both an oscillating neon and valve controlled source, together with correlated data, are shown in Fig. 3 and Table I. Such results are consistent with those of other observers.

E. TYLER

Science Department,
South-East Essex Technical College,
Dagenham, London, England.

[1] Am. Phys. Teacher **5**, 252 (1937).
[2] Tyler, Phil. Mag. **24**, 665(1937).
[3] The method serves equally well with a Quincke tube.

Lantern Slides to Illustrate Interference Patterns Due to Three and Four Collinear Point-Like Sources

PAIRS of lantern slide plates to demonstrate the principle of interferences due to two point-like sources have been described by C. E. Miller[1] and by the author.[2] The latter note was concluded by a statement that attempts were made to prepare plates for producing patterns due to three and four collinear point-like sources, plates that might be used to display the general alterations of interference patterns which accompany the transition from two sources to three and to four, and to illustrate the originating of secondary maximums; but that the results were unsatisfactory, and that for the time being these attempts were not pursued farther. The purpose of this note is to describe the attainment of these objectives.

The method, devices, and manipulations were generally as described in reference 2; namely, a special slide holder, allowing horizontal and vertical sliding movements and azimuthal adjustments for a pair of lantern slide plates, both of them being *now* contact prints of the same original. The original plate was obtained by photographing a suitable rotating pattern which produced a set of concentric, alternately white and black circles representing waves emerging from a point-like source. Since it was believed that the failure to obtain patterns of interferences due to two and to three sources was caused mainly by irregularities of the rotating pattern, several new and different rotating patterns were tried.

The pattern and arrangement which led eventually to success is shown in Fig. 1. A circular wooden disk 161 cm in diameter and 2 cm thick is covered with black velvet

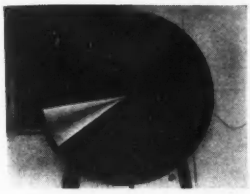


FIG. 1. The pattern-carrying disk.

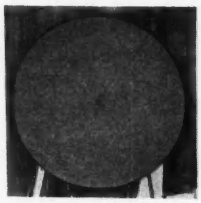
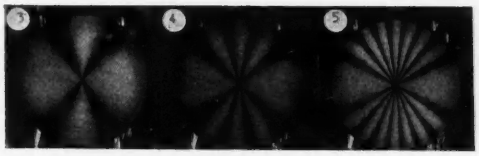


FIG. 2. Wave pattern due to a single source.

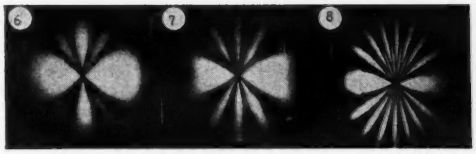
except for a sector of 20° width. Before spreading out the velvet, a suitable piece of drawing paper is pasted into this sector and then subdivided into equilateral circular strips of length 20° and width 4 mm by a series of concentric and equally spaced circular arcs with their centers at the center of the wooden disk. Into each pair of strips a quadrilateral is drawn and inked with India ink, forming thus a fir-tree-like pattern consisting of 98 pairs of branches. This disk is fixed to the axis of an electric motor, the rotating disk photographed, and the series of concentric alternate black and white circles shown in Fig. 2 obtained. From this photograph two contact prints are made, to be used as a first pair of plates illustrating interference patterns and their alterations.

Interference patterns from two, three, and four collinear sources. The pair of plates with their coated sides in contact is inserted in the slide holder and both sets of circles brought into coincidence. The coinciding sets of circles now represent waves emerging from two coalescent point-like sources as in Fig. 2. If one of the plates is made to glide over the other, interference patterns due to two point-like sources are produced, and three such patterns due to two sources separated by two, three, and four wavelengths, respectively, are shown in Figs. 3, 4, and 5.

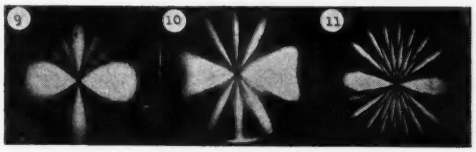
As a next step the interference patterns shown in Figs. 3, 4, and 5 are photographed, and again pairs of contact prints are made to be used now in illustrating interference patterns due to more than two point-like sources. Each pair of corresponding plates, inserted in the slide holder and brought into coincidence, now represents interferences due to two coalescent pairs of point-like sources as in Figs. 3, 4, and 5. If one of the plates is again made to glide over the other, in general, interference patterns due to four collinear, unequally spaced point-like sources are produced. Six special patterns due to three and four equally spaced sources are shown in Figs. 6, 7, 8 and Figs. 9, 10, 11, respectively.



1λ apart 2λ apart 4λ apart
FIGS. 3–5. Interference patterns due to two sources.



1λ apart 2λ apart 4λ apart
FIGS. 6–8. Principal and secondary maximums due to three sources.



1λ apart 2λ apart 4λ apart
FIGS. 9–11. Principal and secondary maximums due to four sources.

By comparing Figs. 6, 7, 8, and 9, 10, 11 with Figs. 3, 4, 5, respectively, it is seen that in the cases of three collinear sources one secondary maximum lies between principal maximums, and that in the cases of four collinear sources two secondary maximums lie between principal maximums. Attempts were made to produce patterns due to more than four collinear point-like sources; but the results were unsatisfactory, the failure probably being due to minute irregularities in the rotating pattern and distortions produced by the photographing process.

The pattern on the rotating disk was executed by Mrs. A. Link, who also made the photographs.

HARALD PERLITZ

Laboratory of Theoretical and Technical Physics,
The University,
Tartu, Estonia.

[1] Am. Phys. Teacher **3**, 75 (1935).
[2] Am. Phys. Teacher **4**, 140 (1936).

As long as intellectual docility is the chief aim, as long as it is esteemed more important for the young to acquire correct beliefs than to be alert about the methods by which beliefs are formed, the influence of science will be confined to those departments in which it has won its victories in the past.—JOHN DEWEY.

DISCUSSION AND CORRESPONDENCE

Dielectrance

HAVING suggested recently[1] the substitution of the term *electromotance* for the misnomer "electromotive force," I am tempted now to suggest *dielectrance* for "dielectric constant," which is not a constant. I have had occasion to use "dielectric constant" many times recently and have grown very dissatisfied with it. This suggestion concerns only the term "dielectric constant" and has nothing to do with the question whether dielectric constant and specific inductive capacity should be regarded as different.

A. WILMER DUFF

Worcester Polytechnic Institute,
Worcester, Massachusetts.

[1] Am. Phys. Teacher **6**, 219 (1938).

Direction of the Electric Current

THERE seems to be a growing tendency among authors of textbooks to reverse the traditional direction of the electric current. There is really nothing against such a change provided it is consistent and thoroughgoing, and provided we are willing to go to considerable trouble. It would probably have been better had "resinous electricity" been called positive and "vitreous," negative from the outset. But, as it is, to say that electricity flows through a wire from the negative to the positive pole of a battery, leads to many absurdities which are pedagogically unfortunate if nothing worse. With such a change the electricity in a wire flows against the potential gradient, up hill as it were. It makes a current give out energy when its direction is that of the electromotive force, and receive energy when its direction is opposite to that of the emf. It makes the accepted explanation of thermoelectric phenomena sound absurd. In short, it makes impossible the rational presentation of a number of phenomena, not to mention the reversal of all the common rules of electromagnetism.

What are the advantages to be gained from this *partial* reform? In electrostatics obviously none. In metallic conduction the proposed change would conform better with the accepted theory, so here there is a slight gain. In electrolysis there is no gain because positive ions are just as important as negative. In discharges through gases under low pressure there is no gain because both positive and negative ions take part in the process. In a highly exhausted tube with heated cathode there is, however, a decided advantage, because the electrons emitted by the cathode are the only ions to be considered and they are much more in evidence than when moving through a wire. Thus we have one genuine advantage to be derived from the proposed change and one slight advantage in the case of metallic conduction. This latter appeals especially to beginners who seem to form a very vivid picture of electrons running around circuits. Most physicists are more cautious and still prefer to talk in terms of a "current" whose direction is immaterial provided it accords with the previous definition of positive and negative charges.

The gains I have noted do not seem sufficiently important to justify an *incomplete* reform with all its annoyances and want of consistency. A *thoroughgoing* reform is another story. We should then start with a North-seeking pole and call it a South pole; a rubbed amber rod would acquire a positive charge; electrons would be positive and protons negative; positrons would have to become negatrons; a body having an excess of electrons would be positively charged, and a deficit would mean a negative charge; the terminals of our meters and sources of emf would have to be remarked, minus for plus and plus for minus; and our textbooks would have to be rewritten. But the old rules of electromagnetism would hold good and electricity would flow down hill and would do work when opposing an emf as it should. Such a clean sweep is at least worth talking about. It is perfectly sound; and yet, as with spelling reform, the trouble involved in making the change might be too high a price to pay for the satisfaction of being rational.

HENRY A. PERKINS

Trinity College,
Hartford, Connecticut.

The Cyclotron and the Elementary Course in Electricity*

THE extensive development of nuclear physics in recent years has led both to fundamental advances in our knowledge of the physical world and to results of great practical interest. Accordingly, the elements of nuclear physics must now be included in the general college course in physics. One could discuss the cyclotron in relation to certain of the newer advances in nuclear physics, and how such material could be incorporated in a general college course, but this would require considerable space. The remarks are therefore confined simply to pointing out how the cyclotron affords effective illustrative applications of the elementary principles of electricity and magnetism. Assuming that the reader is familiar with the general features and operation of the cyclotron, I shall mention three applications:

(1) *The kinetic energy gained by a particle of charge q in falling through a potential difference V is equal to the product Vq.* In the cyclotron, increments of energy are gained by the circulating ions each time they pass from within one of the semicircular hollow accelerating electrodes, called the "dees," to the other.

(2) *Within a hollow conductor containing no charge there is no electric field.* This principle bearing on Faraday's ice pail experiment plays a vital role in the cyclotron; for, while the ions are traveling inside the dees, the charge on the dees reverses sign and thereby the field between the dees reverses direction, "unbeknownst" to the circulating charges inside.

(3) *On a charge q moving with velocity v at an angle θ with a magnetic field of strength H, the force is Hqv sin θ and its direction is at right angles to v and H.* Thus, the ions travel in circles within the accelerating electrodes such that the centrifugal and magnetic forces just balance. From this one can derive immediately that the time for an ion to complete one circle does not depend on the velocity or on the radius of the circular path, but only on q, H, and the mass of the ion. This derivation is a simple and effective illustration of fundamental principles.

Perhaps I may be permitted to make a few further remarks about the elementary course. It is customary in college textbooks to begin the treatment of electricity and magnetism with a discussion of magnetism and electrostatics, and then to embark on current electricity, telling of Oersted's discovery, Ampère's law, and Faraday's law of induction, as separate and apparently unrelated phenomena. It seems to me better to introduce current electricity in the way a modern physicist deals with the subject, to take as a fundamental starting point the experimental fact that the force on a moving charge is described as partly electric and partly magnetic in origin, and of magnitude

$$F=q\left(E+\frac{Hv\sin\theta}{3\times10^{10}}\right).$$

Thus taking the magnetic force on the moving charge as a fundamental experimental fact, one then can derive in a simple and direct fashion: (1) Oersted's discovery that a current has a magnetic field; (2) Ampère's law of the force on a wire carrying a current in a magnetic field; and (3) Faraday's law of induction.

These three derivations from what might be called the fundamental experimental law of the force on a moving charge are simple, direct, and readily understood by the beginner. I hardly need commend for your consideration in an introductory course the desirable features of this approach which so unifies the subject matter.

ERNEST O. LAWRENCE

University of California,
Berkeley, California.

* Abstract of paper presented before the meeting of the A. A. P. T. San Diego, California, May 2, 1938.

The Evolution of Physics

THE term *evolution* may connote different ideas to different people. To the man on the street it may conjure up a monkey; to the biologist it may mean the very gradual building up of complex forms from primitive cells; to some physicists it may suggest the radioactive family tree. But it may mean the evolution or growth of ideas in physics. Even here, however, the theorist may stress one view, the experimentalist, another.

The recent book, *The Evolution of Physics*, by Einstein and Infeld,[1] has been written by theorists. It is highly probable that, on the whole, physicists will feel that the title is a misnomer. Moreover, physicists will take vigorous exception to some of the views there presented. There is a strong tendency to exalt the theorist and to give him the credit for the growth of physics. Here is a typical statement (page 33): "Physical concepts are free creations of the human mind." The fact is that physicists are slaves; they are under compulsion to form concepts in accord with experimental results. One notable example will suffice. Planck, in order to account for the experimental data regarding black-body radiation, found it necessary to make an unwanted, seemingly absurd, assumption; namely, that radiant energy is emitted and absorbed in bundles. Thus came into existence the quantum idea, the most important concept of the past forty years, a concept of overwhelming importance.

Again we have (page 9): "Human thought creates an ever-changing picture of the universe. Galileo's contribution was to destroy the intuitive view and to replace it by a new one." Here it seems to be implied that our picture of the universe may be formed merely by thinking about it. But we can hardly claim that a picture so formed would necessarily have any place in the evolution of physics. Our waste baskets have received many communications presenting pictures of the universe formed by thinkers. As to Galileo, nowhere in the book is it brought out that the great contribution made by Galileo was the idea of measurement, of exact measurement, and of concepts depending upon experimental evidence.

Physics is an experimental science. Its evolution has been due to the exhaustless energy of experimenters. But the authors seem to regard experimentation without a pre-existing theory as rather useless. Consider, for example, the statement on page 73, "It is hardly possible to imagine such experiments [electrical] performed in accidental play without the pre-existence of more or less definite ideas about their meaning." What pre-existing theory did Roentgen have regarding x-rays, the existence of which was unsuspected? Did the Curies preconceive the astounding properties of radium or vision the universe that was to be opened up by its discovery? As a further evidence that the authors regarded the growth of physics to be chiefly along theoretical, not along experimental, lines it may be noted that the name of Rutherford—the greatest experimental physicist since Faraday—occurs only once (page 272), and the great domains which his researches opened up are ignored.

Again we ask, what is meant by the evolution of physics? What is the realm of the physics of today? In that realm we would at least list the great discoveries of recent years—the discovery of x-rays, of the electron, of radium, of the radioactive transmutation of the elements as established by Rutherford and Soddy, of the energy states of an atom and the resulting laws regarding atomic spectra originating with Bohr, of the nuclear nature of the atom as brought out by Rutherford, of the significance of the atomic number as established by Rutherford and Moseley, of the wave and quantum character of x-rays, of the isotopic variations of elements as established by Thomson, Aston, Dempster, etc., of the development of the electron tube and its vast application to science, industry, and human activities, of the Zeeman, Compton, and Raman effects and their complete accord with the quantum view of radiation; the new universe opened up by cosmic-ray phenomena, the Rutherford-Geiger-Müller counter and its enormous sensitivity increasing a million-fold our ability to detect electrified

particles, our new engines, especially the Lawrence Livingston cyclotron for hurling atoms with enormous energies at other atoms, the new physics and chemistry opened up by the artificial transmutation and radioactivity of the elements.

After contemplating this realm, we wonder whether physical concepts are the free creations of the human mind.

GORDON FERRIE HULL

Dartmouth College,
Hanover, New Hampshire.

[1] (Simon and Schuster, 1938).

Ohm's Law and Kirchhoff's Second Law

IN his excellent discussion of Ohm's law,[1] L. M. Alexander follows Planck's development of the circuit equations for the stationary electromagnetic field and identifies electromotive force with contact potential. The following alternative treatment, beginning with a broader definition of emf, reveals a serious objection to the use of any relation between emf's and resistance-current products as a fundamental law. The definitions and development are adapted from the text by H. C. Barker and M. R. Harkins.[2]

In the following discussion, we shall understand an *electrical source* primarily to be a place of transformation of nonelectrical energy into electrical potential energy. The characteristic property of such a source, electromotive force E, is the ratio of the energy transformed to the quantity of electricity simultaneously raised in potential and carried through the circuit; symbolically, $E=dW/dq$. In an *electrical sink* the reverse transformation occurs with a concomitant drop in potential e.

To achieve generality we shall extend our conception of sources and sinks to include components of circuits where energy is stored or released from storage, as by a conductor which has appreciable inductance or by a condenser. It does not matter whether we call such a part of a circuit a source or a sink, provided that the corresponding quantity dW/dq in our equations has at each instant the correct algebraic sign.

A reversed source exerts a "back emf" and is in effect a sink. It is convenient, however, to indicate reversal of a source by change of the sign of E, rather than to classify the reversed source as a sink.

In general the sources cannot be separated physically from the sinks, as any source, such as a battery in which there is current, is simultaneously a sink, due to unavoidable transformation of some electrical energy into heat.

Imagine a small quantity of electricity Δq carried around a closed path in a circuit, with an attendant conversion of energy $\Sigma\Delta W$ in the sources and $\Sigma\Delta w$ in the sinks. Since the energy is conserved, we may write

$$\Sigma\Delta W=\Sigma\Delta w. \qquad \text{(closed path)} \quad (1)$$

Dividing both sides of this equation by Δq and letting Δq approach zero as a limit, we obtain

$$\Sigma E=\Sigma e. \qquad \text{(closed path)} \quad (2)$$

In words, *around any closed path in a circuit the sum of the electromotive forces of the sources equals the sum of the drops in potential in the sinks.* In the text cited,[2] this statement is called Kirchhoff's second law. It is, in view of Eq. (1) in its derivation, clearly a form of the law of conservation of energy for it expresses the fact that the energy supplied at the sources equals the energy withdrawn at the sinks. It is of the utmost generality.

Any relation between emf's and products of resistance and current, RI, is unsuited for use as a fundamental law because it can be resolved into two or more separate principles. To illustrate this, consider Alexander's second and third numbered equations,[3] namely,

$$I=\Sigma E/\Sigma R, \qquad \text{(closed path)} \quad (3)$$

sometimes called Ohm's law, and

$$\Sigma E=\Sigma IR, \qquad \text{(closed path)} \quad (4)$$

usually called Kirchhoff's second law. Either of these equations contains two basic concepts,

$$\Sigma E=\Sigma e, \qquad \text{(closed path)} \quad (2)$$

$$e=IR. \quad (5)$$

We have already discussed Eq. (2). We may regard Eq. (5) as an independent empirical relation and call it a symbolic expression of Ohm's law. Alternatively, introducing the symbol t for time, we may assume as the empirical relation,

$$dw=RI^2dt, \quad (6)$$

called Joule's law and here written for convenience in differential form, as the current may be variable. Combining Eq. (6) with a defining equation for quantity of electricity,

$$dq=Idt, \quad (7)$$

we obtain Eq. (5); namely, $dw/dq=e=IR$. Eq. (5) may be expressed verbally: *In any sink in which the energy conversion is in accordance with Joule's law, the drop in potential equals the product of the current and the resistance.* This form of Ohm's law resembles Alexander's category (D), but is more useful as it may apply to a sink which is associated with a source, as in the case of the drop in potential due to internal resistance of a battery.

The arbitrary nomenclature, Kirchhoff's second law for Eq. (2) and Ohm's law for Eq. (5), is open to objection on historical grounds. The historical form of Kirchhoff's second law is equivalent to Eq. (4), whose double content has been indicated above. Ohm did not enunciate any single relation which we can unambiguously call his law.[4] The form here adopted is not identical with any of the several principles which he expressed. These changes have been recommended here because rigid adherence to tradition seems less important than that reduction of fundamental laws to lowest terms, which is an essential characteristic of scientific method.

The writer is indebted to Professor Harold C. Barker, with whom he discussed the ideas here expressed.

R. D. SUMMERS

Randal Morgan Laboratory of Physics,
University of Pennsylvania,
Philadelphia, Pennsylvania.

[1] Am. Phys. Teacher **6**, 68 (1938).
[2] *A Textbook in Physics* (Pitman, in press).
[3] Reference 1. The notation has been changed from J and w to I and R, respectively.
[4] See G. S. Ohm, *Gesammelte Abhandlungen* (Barth, Leipzig, 1892) or J. C. Shedd and M. D. Hersey, *The History of Ohm's Law*, Pop. Sci. Mo. (now Sci. Mo.) **83**, 599 (1913).

Proceedings of the American Association of Physics Teachers

THE SAN DIEGO MEETING, JUNE 24, 1938

THE first meeting of the American Association of Physics Teachers on the Pacific Coast was held in San Diego, California, June 24, 1938, in connection with the 22nd annual meeting of the Pacific Coast Division, American Association for the Advancement of Science and Associated Societies. The registration of those in attendance lists 16 members and 26 non-members. The following members registered:

M. S. Allen, Long Beach Junior College; W. P. Boynton, Oregon State College; H. C. Burbridge, Fresno State College; N. W. Cummings, San Bernardino Junior College; L. E. Dodd, University of California at Los Angeles; P. S. Epstein, California Institute of Technology; G. W. Gardiner, Jr., New Mexico State College; W. W. Gayman, Sacramento Junior College; L. W. Jones, University of Redlands; W. H. Jordan, University of South Dakota; H. A. Kirkpatrick, Occidental College; Paul Kirkpatrick, Stanford University; A. A. Knowlton, Reed College; E. O. Lawrence, University of California; B. B. Watson, Arizona State Teachers College; D. L. Webster, Stanford University.

At a noon meeting in the Cafe del Rey Moro, Balboa Park, Professor D. L. Webster, a former president of the Association, gave a stimulating impromptu talk, and there was also an informal discussion of Association activities and plans in the western part of the country.

The session for the presentation of papers convened at 1:30 P. M. in the Auditorium, House of Hospitality, Balboa Park, with Professor Webster presiding. The following invited papers were heard:

Equations of State for Physics Teachers. W. P. Boynton, *Oregon State College, Corvallis, Oregon.*

The Flying Laboratory. A. A. Knowlton, *Reed College, Portland, Oregon.*

The Physics Problem in High Schools. Roy W. McHenry, *Union High School, Escondido, California.*

Mathematics in the Secondary School as Related to College Physics. Paul S. Epstein, *California Institute of Technology, Pasadena, California.*

Relation of the Cyclotron to Present-Day Courses in College Physics. E. O. Lawrence, *University of California, Berkeley, California.*

The remainder of the session was devoted to 10-minute contributed papers as follows:

1. The Evaluation and Guidance of Functional Student Progress. MYRON S. ALLEN, *Long Beach Junior College, Long Beach, California.*—Lack of an adequate plan of evaluation of student progress is a main reason why so many college students dislike or shun physics; the average student recognizes that in few life situations will he be called upon to apply generalizations through equations, and yet, in most courses, his grade will depend upon his agility in performing that task. With respect to the broad problem of evaluation we have come to the following conclusions: (1) the primary step is to understand thoroughly the major objectives of education in terms of the specific aims of a particular college and the desired changes in the behavior of the individual student; (2) the process of evaluation is not a mere perfunctory inventory of unrelated student achievement, but is continuous and comprehensive; it is an integral part of, grows out of, and results in the revision of the curriculum; (3) it involves defining the behavior to be evaluated, selecting situations in which the desired behavior may be evidenced, developing a record of the behavior which takes place in these situations, and determining the type and degree of changes brought about by the curriculum; (4) the emerging role of evaluation, including examining, is that of guidance; (5) the technics and criterions employed in evaluating behavior should be pertinent to the objectives of the curriculum as it is conceived in a particular, local situation. True objectives do not tell "how and why," but "to what end." The universal wants of mankind, which constitute the major educational objectives, are, briefly: (1) preservation or acquisition of physical adequacy; (2) participation in a satisfying home life; (3) preparation for, and participation in, work that is satisfying and economically adequate; (4) satisfying participation in community life; (5) satisfying participation in recreation; (6) achieving a satisfactory relationship with mankind and the "power of the universe." An evaluation program which considers these as the objectives of education must recognize individual differences in students and measure individual progress by methods that will make effective guidance replace the customary post-mortem. While the maintenance of standards may still have a minor place in evaluation, it should be largely replaced by diversified standards for individual functional progress.

2. An Electric Circuit Containing a Spark Gap. W. P. BOYNTON, *University of Oregon, Eugene, Oregon.*—This paper discusses the phenomena and theory of the typical spark, of nonoscillatory and oscillatory discharges of a condenser through a spark gap, and of two tuned circuits such as those employed in the older "spark" wireless telegraphy. The graph of the oscillatory discharge of a condenser exhibits a linear rather than an exponential envelope. In two tuned circuits, the envelope of the graph of the primary current is sensibly linear, while that for the secondary is approximately a sine curve which changes to the exponential form as its energy is dissipated after the spark is quenched.

3. An Improved Method for Mapping Electric Fields. HARRY C. BURBRIDGE, *Fresno State College, Fresno, California.*—In the usual method for mapping electric fields in the student laboratory, two fixed electrodes, between which a pulsating field is maintained by an induction coil, dip into a thin layer of the electrolyte contained in a glass-bottomed tray; another electrode, used as a reference, is then set at different points and an equipotential line traced for each point with a movable electrode connected to the reference through headphones. If, instead, 25-v a.c. is used for the field, and the headphones are replaced by a copper oxide rectifier and portable galvanometer, much more accurate results are obtained in a far shorter time and without the discomfort the long use of headphones gives.

4. A Small Optics Shop as an Aid in Conducting an Intermediate Laboratory Course in Optics. G. G. KRETSCHMAR, *Walla Walla College, Walla Walla, Washington.* (*Read by Harry A. Kirkpatrick.*)—Equipment for performing the ordinary operations of preparing and polishing optical surfaces has been collected and developed. With it, a student working 10 hr/wk has been able to produce a number of excellent prisms, interferometer plates, and other optical parts for use in the optics laboratory. The equipment, which can be built in an ordinary departmental shop, consists of a small polishing machine, a cast iron lapping disk, a cast iron surface plate for fine hand-lapping, and a small edging wheel. An evaporating equipment is used for metallizing surfaces, and a small mercury arc for testing.

5. An Approach for Introducing the Characteristics of Measurement. L. E. DODD, *University of California at Los Angeles, California.*—In engineering and scientific work involving high precision and reliability, repeated measurements of a particular property are generally required. Although the characteristics of such series of measurements are treated in the theory of probability, it is not necessary for the student to master this theory in order to be introduced to the essential characteristics of measurement. In the present paper these essential characteristics are defined and discussed, and then illustrated by presenting 10 groups of data that represent estimates, made by individual students, of length, volume, angle, ratio of lengths, and ratio of areas. These estimates were made by 8 different freshman classes in engineering physics in as many semesters over a period of 7 years. The number of students in a class ranged from 21 to 197. The graphs of these data exhibit the distribution trends of probability curves. The main characteristics of measurement are also evaluated graphically and used to illustrate what may be expected in any series of observations. Thus to have a class estimate physical quantities consumes relatively little time, arouses interest in measurement, and has the advantages that it involves both individual and group activity.

6. Hydrodynamic Apparatus for Demonstrations in Radioactivity. J. L. BOHN AND F. H. NADIG, *Temple University, Philadelphia, Pennsylvania.* (*Read by Paul A. Kirkpatrick.*)—The complete paper will appear in the December issue.

During the session Professor L. E. Dodd read a letter of greeting from President F. K. Richtmyer to the members of the Association on the west coast, and a progress report on the A. A. P. T. Manual of Demonstrations, prepared by its editor, R. M. Sutton. The papers prepared by Professors Boynton, Burbridge, and Dodd were read by title, since the half-day session did not provide sufficient time for presentation of all the papers scheduled.

Much credit for the success of the meeting goes to Clinton G. Abbot, chairman of the general A. A. A. S. committee, who gave prompt and detailed attention to the various requests of the Association for information and facilities. The program committee for the meeting consisted of H. A. Kirkpatrick, R. H. Tileston, and L. E. Dodd. Arrangements for the luncheon were made by M. S. Allen.

L. E. DODD, *Chairman, Program Committee.*

THE TORONTO MEETING, JUNE 24–25, 1938

THE American Association of Physics Teachers met jointly with the American Physical Society at the University of Toronto, Toronto, Canada, on Friday and Saturday, June 24–25, 1938. The registration of those in attendance lists 49 members of the Association and 10 nonmembers. The following members registered:

R. L. Allen, University of Western Ontario; Gladys Anslow, Smith College; R. H. Bacon, New York University; G. B. Banks, Niagara University; E. F. Barker, University of Michigan; J. W. Beams, University of Virginia; D. M. Bennett, University of Louisville; R. A. Beth, Worcester Polytechnic Institute; H. Louisa Billings, Smith College; Isabel Boggs, Randolph-Macon College; J. L. Bohn, Temple University; H. A. Boorse, Columbia University; G. Harvey Cameron, Hamilton College; Edna Carter, Vassar; John L. Clark, Chapman Technical High School (New London, Conn.); Elizabeth Cohen, University of Toronto; T. D. Cope, University of Pennsylvania; Henry Crew, Northwestern University; V. E. Eaton, Wesleyan University; Henry A. Erikson, University of Minnesota; Willena Foster, University of Western Ontario; W. P. Gilbert, Lawrence College; Monica Helea, Vassar; John R. Hobbie, Skidmore College; Elmer Hutchisson, University of Pittsburgh; H. J. C. Ireton, University of Toronto; A. T. Jones, Smith College; E. H. Kennard, Cornell University; Elizabeth R. Laird, Mount Holyoke; W. C. McQuarrie, Lafayette College; W. H. Michener, Carnegie Institute of Technology; D. C. Miller, Case School of Applied Science; Floyd W. Morris, Louisiana State University; R. A. Patterson, Rensselaer Polytechnic Institute; Anna W. Pearsall, Hamilton, N. Y. High School; G. B. Pegram, Columbia University; Robert L. Petry, University of the South; W. C. Priest, St. Lawrence University; F. K. Richtmyer, Cornell University; Alfred Romer, Whittier College; H. C. Roys, University of Oklahoma; W. L. Severinghaus, Columbia University; N. F. Smith, The Citadel; S. Sonkin, College of the City of New York; Ross Spangler, State Teachers College, La Crosse, Wis.; M. N. States, Central Scientific Company; John T. Tate, University of Minnesota; Dorothy Weeks, Wilson College; M. W. Zumansky, College of the City of New York.

A joint session of the two societies on Friday morning, June 24, was devoted to an address of welcome by President Cody, of the University, and an invited paper, entitled "Methods and Objectives of Teaching Physics in England and in America," by Professor John Satterly, University of Toronto.

On Friday afternoon and Saturday morning, members of the Association attended the session of contributed papers and the symposium of the American Physical Society. After the sessions on Friday a reception for the members of the two societies and their friends was given by President and Mrs. Cody on the lawn of the Royal Ontario Museum. In the evening a joint dinner was held in the Great Hall of Hart House. The after-dinner speakers were President Cody, and Professors Richtmyer, Tate, and Satterly.

Other events of the meeting included an elaborate exhibit of 59 laboratory and demonstration experiments and apparatus, arranged jointly by the University Department of Physics and the departments of nearby colleges and secondary schools; an exhibit by Professor E. C. Burton of liquid helium in the Cryogenic Laboratory of the

University; visits to the mechanics and heat laboratory, arranged as for use by an elementary class; and excursions on Saturday afternoon to the David Dunlop Observatory, the Toronto harbor and airport, and station CBL of the Canadian Broadcasting Corporation.

Meeting of the Executive Committee. The executive committee met on Friday afternoon in the library of the McLennan Laboratory. Members present were F. K. Richtmyer, D. M. Bennett, and T. D. Cope. M. N. States attended by invitation, as the representative of the treasurer, P. E. Klopsteg.

It was voted that the "service charge" which the Association pays in support of the American Institute of Physics be increased from the usual rate of 15 percent to 20 percent during 1938. Preliminary plans were made for the next annual meeting, to be held in Washington, D. C., on December 29–30. The committee on awards was authorized to secure dies for a suitable medal to be presented to recipients of the annual award for outstanding contributions to the teaching of physics. The treasurer reported that of 862 members in good standing at the end of 1937, all but 110 had paid dues for 1938. The secretary was instructed to request that petitions for summer meetings of the Association during 1939 be in his hands before December 28, 1938.

THOMAS D. COPE, *Secretary*

The Forthcoming Washington Meeting of the American Association of Physics Teachers

THE eighth annual meeting of the American Association of Physics Teachers will be held in Washington, D. C., on Thursday and Friday, December 29–30, 1938. Parallel sessions of the Association and the American Physical Society will be held on Thursday morning, and a joint session of the two societies, on Thursday afternoon. Friday will be devoted exclusively to sessions of the Association. At the annual dinner to be held jointly with the American Physical Society, the presentation will be made of the third A.A.P.T. Award for Notable Contributions to the Teaching of Physics. The Wardman Park Hotel will be headquarters for both societies.

Members who wish to contribute papers should send the title and abstract as soon as possible to the secretary, Professor Thomas D. Cope, Randal Morgan Laboratory of Physics, University of Pennsylvania, Philadelphia, Pa. Contributed papers are limited to 10 minutes. *A paper will not be accepted unless a 100–300 word abstract, prepared in a form suitable for publication, is in the hands of the Secretary by November 25.* The copy must be typewritten, double spaced, and should be prepared in the same general form as the abstracts which appeared in the February, 1938, issue of *The American Physics Teacher*, pages 41–45.

Petitions for Summer Meetings During 1939

PETITIONS for meetings of the American Association of Physics Teachers to be held during the summer of 1939 must be submitted in advance of the annual meeting, according to an action taken by the Executive Committee at its last meeting. The petitions and as much supporting information as possible should be in the hands of the Secretary, Professor T. D. Cope, by December 28, 1938.

Activities of the District of Columbia and Environs Chapter

THREE meetings of considerable interest were held during the academic year 1937–38 by the recently organized District of Columbia and Environs Chapter of the American Association of Physics Teachers.

At a meeting held on October 27, at George Washington University, demonstrations were given of a magnetic heat motor, by George D. Rock, of Catholic University; a graphic device for teaching electromotive force and potential difference, by W. L. Cheney, of George Washington University; and a ballistic pendulum, by R. L. Feldman, of Roosevelt High School. A report on the fall meeting of the Pennsylvania Conference of College Teachers was given by Thomas B. Brown, of George Washington University. The meeting ended with refreshments served at the College Inn.

The annual meeting for the election of officers was held at Catholic University on February 7. Thomas B. Brown, of George Washington University, was elected president; E. J. Kolkmeyer, of Georgetown University, and George D. Rock of Catholic University, were made members of the executive committee; R. L. Feldman, of Roosevelt High School, continues as secretary-treasurer, the term of this office being two years. The meeting closed with an exhibition of various phenomena in the fields of ultrasonics and nuclear physics by the physics staff of Catholic University. Refreshments were served.

The last meeting of the year, held on May 23, took the form of a visit to the nuclear research laboratory of Carnegie Institution's department of terrestrial magnetism. The members of the chapter were the guests of Dr. M. A. Tuve and his associates.

The attendance of members and guests ranged from 14 at the first meeting to 25 at the last.

POSTVIEWS OF PHYSICS TEXTBOOKS

A Textbook of Physics. CHARLES A. CULVER, professor of physics in Carleton College. 826 p., 525 fig., 14×22 cm. *Macmillan*, **$4**.

In Professor Culver's textbook on general physics the topics have been selected with care and, for the most part, are so presented that the student is able to follow the treatments without particular difficulty. The discussion is often more detailed than is common in a book of this level. As is stated in the Preface, ". . . a conscious effort has been made to treat with special care those concepts and laws (often basic ones) which experience shows are difficult for many students to grasp." One frequently senses this painstaking, conscious effort of the author, which results in many repetitions and in statements that are unduly prolix and diffuse. Indeed, the reader is tempted at times to try to condense the material before him into a more compact form.

In the first 16 pages of the book, the students encounter linear motion, circular motion, constant and variable velocities, constant acceleration, force, weight, mass, torque, momentum, moment of inertia, and the law of gravitation. Although the correlation here of linear and angular relations is very good, this initial chapter is a tough morsel for the beginner to digest in one or two assignments. The relatively difficult concept of moment of inertia, introduced by the none too illuminating statement that it is "the effectiveness of the inertia of a body to prevent a change in angular velocity," might have been withheld until the student has become a little more seasoned, and when it could have been introduced more naturally and precisely while considering kinetic energy of rotation.

The division on heat is made interesting by the addition of historical material often omitted by writers of textbooks; indeed, frequent historical references constitute an excellent feature of the book as a whole. A brief discussion of quantum theory in connection with heat phenomena serves to introduce some of the more recent ideas. The chapter on the physics of the atmosphere is appreciated by the students.

Light, which follows mechanics and heat, is not preceded by any discussion of wave motion, as such, although references are made to related ideas in mechanics when wave concepts are needed. The treatment of light is quite complete and, as a rule, clear. Although the illustrations in the book are generally well chosen and clear, too many diagrams in the chapters on reflection, refraction, and lenses are poorly or erroneously drawn. There seems to be no excuse for the misstatement about Römer's method for determining the speed of light; namely, that "the time interval which elapsed between the successive eclipses of a given satellite when the earth was at E' was about 1000 seconds greater than when a corresponding set of observations were made when the earth was at E." On page 360, the focusing property of a parabola is erroneously given. Indeed, there is a larger number of misstatements and misprints than one would expect, even in a first edition. For instance, one reads that Galileo was experimenting in 1663; Davy and Seebeck made certain discoveries in 1881 and 1882, respectively; the area of the image will vary inversely as the square of the focal length; trivalent elements carry three electrons; the watt-hour is equivalent to 3600 amp sec; etc.

Whether the author's use of the electron current in place of the conventional electric current is wise, remains to be seen. Before the full benefits of such a change can be realized, it would appear that at least the units now defined in terms of the positive charge and pole should be redefined. The new convention confuses the student when he applies Kirchhoff's second law, and this confusion is encouraged by the author's illustrative example; for, although the law is stated in the usual form, Σ e.m.f. $=\Sigma RI$, the form actually employed in the example is Σ e.m.f. $+\Sigma RI=0$. In one or two other cases, the author unconsciously reverts to the old convention. Included in the division on electricity and magnetism is a generous discussion of electronics, electromagnetic watts, and radioactivity.

The treatment of sound is entirely too brief and it leaves us with the impression of having been hastily done. The tendency in most general textbooks to neglect this technically and scientifically important branch of physics is unfortunate, we think. In the present book, vibrating strings and air columns are analyzed without mention of the fundamental phenomenon of stationary waves.

Suitable illustrative problems are introduced frequently throughout the text but problems for the students to solve are provided in only about two thirds of the chapters. While it is true that "Additional problems . . . will doubtless suggest themselves to the experienced teacher," time during a class hour to dictate problems is scarce and mimeographed supplementary lists should be unnecessary. This defect of the book has been remedied, however, in that the author has prepared a supplementary list of problems, in a separate pamphlet. Many of the problems are so simple in character that the student can blindly substitute in a formula. The data in a number of the problems are incomplete. Answers do not appear in the book, but are furnished separately to instructors; they need thorough revision, for approximately a fifth of them are incorrect.

Four appendixes give the simple trigonometric relations, a derivation of the formula for the coefficient of rigidity, and tables of trigonometric functions and four-place logarithms. A very satisfactory index of 14 pages completes the book.

W. W. COLVERT, *Armour Institute of Technology*
L. W. HARTMAN, *University of Nevada*
A. P. R. WADLUND, *Trinity College*

RECENT PUBLICATIONS AND TEACHING AIDS

Textbooks for General College Physics

A First Course in Physics for Colleges. Robert Andrews Millikan, director of the Norman Bridge Laboratory of Physics, Henry Gordon Gale, Professor of Physics, University of Chicago, and Charles William Edwards, Professor of Physics, Duke University. Rev. ed. 787 p., 96 plates, 592 fig., 34 tables, 14×21 cm. *Ginn*, $4. The 1928 edition of this text has been extensively revised to take into account important changes in physical knowledge which have received general acceptance during the past decade, and the many new engineering and commercial applications of the same period—air conditioning, streamlining, sound pictures, wire-photo transmission, short-wave radio, and so on. A large assortment of problems of widely varying difficulty is provided, so that the course can be adapted to the different abilities and preparation of the students who enter college today. A stated purpose of the authors is "to meet the urgent need for a text which may profitably be presented to any freshman without the omission of a single paragraph." The illustrations are good, particularly the many full-page reproductions of photographs.

Reference Books for First Courses

New World Picture. George W. Gray. 415 p., 50 fig., 14×21 cm. *Little, Brown*, $3.50. A remarkably reliable and expertly written popular account of the accomplishments of modern physics and astrophysics, by the author of *The Advancing Front of Science* [Am. Phys. Teacher **6**, 49 (1938)].

Photography. C. E. Kenneth Mees, Director of Research and Development, Eastman Kodak Co. 243 p., 45 fig., 63 plates, 14×21 cm. *Macmillan*, $3. Nontechnical but authoritative and comprehensive, this excellent account of photography had its origin in a series of Christmas lectures given by the author at the Royal Institution in London. These Christmas lectures for young people, begun more than a century ago by Faraday and since continued by a succession of eminent scientists, always consist largely of experimental demonstrations; these have necessarily been replaced in the book by descriptions and illustrations. The main subjects discussed are the history of photography, the manufacture of photographic materials, modern photographic practice, image formation, the reproduction of tone values, motion pictures, color photography, and various applications of photography. Especially interesting is the historical chapter, based as it is mostly on the author's first-hand knowledge of the development of the art and on information gained during his earlier association with the pioneer firm of Wratten & Wainwright. The photographs and diagrams are exceptionally fine, and the typography and book work, excellent.

Advanced Textbooks and References

An Introduction to Riemannian Geometry and the Tensor Calculus. C. E. Weatherburn, Professor of Mathematics, University of Western Australia. 202 p., 13×21 cm. *Cambridge Univ. Press*, $3.75. The purpose of this book is to bridge the gap between differential geometry of Euclidean three-dimensional space and the more advanced work on differential geometry of generalized space, now so important because of its applications to general theories of relativity. The geometrical aspect is emphasized. The tensor calculus of Ricci and Levi-Civita is employed, and hence the book provides an introduction to this calculus as well as to Riemannian geometry.

Thermodynamics. Enrico Fermi, Professor of Physics, The University of Rome. 170 p., 22 fig., 15×23 cm. *Prentice-Hall*, $3. The introductory treatment of pure thermodynamics afforded by this text is an elaboration upon a course of lectures delivered at Columbia University in 1936. The first four chapters discuss the fundamental concepts and principles in much the usual manner, and the subsequent chapters deal likewise with thermodynamic potentials, gaseous reactions, dilute solutions, and the entropy constant. Because of its brevity and conciseness, the book should prove most useful as a basic outline for a course in which time is available for considerable classroom discussion and collateral reading.

Dynamics, Part II. A. S. Ramsay, President of Magdalene College, Cambridge. 355 p., 100 fig., 14×22 cm. *Cambridge Univ. Press* and *Macmillan*, $4.50. This book is a continuation into a more advanced field of the author's *Dynamics, Part I*. It amplifies the dynamics of a particle, extending it to three dimensions, and gives a much fuller treatment of rigid dynamics than was possible in Part I. In the many examples throughout the text, and in the treatments of central orbits, tangential and normal accelerations, and the particle in three dimensions, the author has drawn freely on Besart's *Treatise on Dynamics*, the last edition of which he prepared for publication twenty years ago but which has long been out of print. Of interest is the author's comment in the Preface:

> It is hardly possible to ignore the present-day fashion of using vectors in dynamics; and, to meet the needs of students who wish to know how to obtain the fundamental equations of dynamics by vectorial methods, I have introduced the subject and taken it thus far in an appendix [of 19 pages]. I doubt whether it is a fashion which has come to stay, and I am unwilling to require all readers of this book to use vectors.

Some 70 worked examples are included in the text.

The Fundamental Principles of Quantum Mechanics. Edwin C. Kemble, Professor of Physics, Harvard University. 629 p., 27 fig., 15×23 cm. *McGraw-Hill*, $6. Professor Kemble's new text on the basic technic of non-

relativistic quantum mechanics affords the student the opportunity to obtain much more than a surface knowledge of the theory. The treatment is inductive in character, the applications of the theory being interwoven with the development of the mathematical structure. The operational point of view is emphasized, and consistently so. Believing that there is need for a treatment that does not gloss over the defects of the theory, the author has sought to bridge the gap between the usual formulations, in which the defects are minimized in order to present a compact and attractive outline, and the rigorous formulation in von Neumann's *Mathematische Grundlagen der Quantenmechanik*, which is too difficult and exacting for the average graduate student. The first two chapters present the early history of the theory and the wave-particle dualism of the atom; the third chapter, the Schrödinger equation for one-dimensional problems and the Kramers-Wentzel-Brillouin approximate solutions; the next five chapters, the mathematics of quantum theory; the next four chapters, the theories of measurements, matrices, perturbations, and radiation; the final two chapters, applications to the general problem of complex atomic spectra.

History of Science

The Role of Scientific Societies in the Seventeenth Century. Martha Ornstein. Ed. 3. 326 p., 14 plates, 16×22 cm. *Univ. of Chicago Press*, $3. The subject of this well-known and useful study is the scientific societies of the seventeenth century, whose unmistakable and magnificent achievement it was, "not only to put modern science on a solid foundation, but in good time to revolutionize the ideals and methods of the universities and render them the friends and promoters of experimental science instead of the stubborn foes they had so long been." The study was privately printed as a Doctor's dissertation in 1913, two years before the death of the author. As time went on no other study appeared to supplant it and hence, in 1928, a second edition was published in the form of a memorial to the author. In the present edition, 14 full-page plates of a historical character are included. The book is fully documented, has much to say about the work of individuals as well as of the societies, and is not entirely confined in its treatment to the seventeenth century. It has proved itself of great value to students of scientific history and to those who wish to add to their understanding of the manner in which modern science got under way.

Methodology and Philosophy of Science

The Grammar of Science. Karl Pearson. 382 p., 25 fig., 4 tables, 10×17 cm. *Everyman's Library, Dutton*, 90 cts. This famous critical survey of the fundamental concepts of the sciences has heretofore not been available in an inexpensive edition. The physical portion of the *Grammar*, which Pearson himself is said to have regarded as the most important part, taken in conjunction with Mach's two books on mechanics and heat (the latter still untranslated), and J. H. Poincaré's three books on the foundations of science are almost indispensable reading for anyone who wishes to acquire a basis for understanding modern physical concepts, methods, and trends. Despite the pioneer character of these works, their outlook is so sane and their insight so penetrating that they have served to clear up a great mass of misconceptions concerning the meaning, implications, and purposes of classical physics which had accumulated up to their time—misconceptions that still tend to persist simply because these books and subsequent inquiries stimulated by them have not received wide enough attention. In the present reissue of the *Grammar*, it was found impracticable to reproduce the whole of the fourteen chapters which appear in one or the other of the original 1892, 1900, and 1911 editions. Rather than attempt the dangerous task of contracting the text, the editors decided to reproduce the ten chapters of the 1892 edition, using, however, the improved text of 1900. Thus are included, besides the Introduction, the chapters on the Facts of science, Scientific law, Cause and effect, and probability, Space and time, Geometry of motion, Matter, Laws of motion, Life, and Classification of the Sciences. Summaries of the four omitted chapters are included, however, and also the prefaces of all three editions.

Motion Picture Films

Safety Glass. 16 or 35 mm, silent, 30 min. *Bureau of Mines Experiment Station* (4800 Forbes St., Pittsburgh), loaned gratis. Reel 1 shows how safety glass is made, and then poured, annealed, cut, and ground. Reel 2 shows how it is polished and then installed in a Ford automobile.

Earth and Its Seasons. 16 mm, sound film, 10 min. *Garrison Film Distributors* (1600 Broadway, New York), rental or sale. Animated diagrams, models, and actual phenomena that illustrate seasonal changes as affected by the tilt of the earth's axis, the rotation, revolution, and curvature of the earth, and the atmosphere.

They Know How. 16 and 35 mm, sound film, 30 min. *General Electric Co.* (Nearest G. E. appliance dealer), loaned gratis. A trip through the G. E. refrigerator factories.

Exhibits

Celotex Products. *Celotex Corporation* (Public Relations Dept., 919 Michigan Ave., Chicago), gratis. Samples of Acousti-Celotex, Celotex Insulation Board, and Cemesto Celotex. While this company does not have demonstration experiments available, it is willing to cooperate to a reasonable extent on worthwhile projects.

Booklets and Catalogs

DuPont Publications. *E. I. duPont de Nemours & Co.* (Fabrics Div., Fairfield, Conn.), gratis. Three booklets, entitled *Efficient Mine Ventilation*, *Tunnel Construction Ventilation*, and *Auxiliary Ventilation for Metal Mines*.

America's Largest Electrical Workshop. 20 p., 27 photographs, 13×20 cm. *General Electric Co.* (Schenectady, N. Y.), gratis. Brief description of the Schenectady plant and activities.

DIGEST OF PERIODICAL LITERATURE

Apparatus and Demonstrations

Measurement of grid currents in thermionic valves. E. W. Wilcox; *J. Sci. Inst.* **15**, 137, Apr., 1938. In this method of measuring grid currents of the order 10^{-9} amp, the usual circuit for measuring tube characteristics is modified by inserting a known high resistance R with short-circuiting switch into the grid circuit. Plate current values are recorded for a series of grid potentiometer voltages first with R short-circuited, then with R in the circuit, the potentiometer being adjusted to give the same plate current in both cases. If V and V' are the two potentiometer voltages, the grid current is $(V'-V)/R$. The best values of R vary between 10 and 1000 megohms, depending on the values of the grid current and tube mutual conductance.—H. N. O.

A note on the measurement of capacitance by ballistic methods. N. F. Astbury and L. H. Ford; *J. Sci. Inst.* **15**, 94, Mar., 1938. This method for measuring a capacitance ballistically in terms of an adjustable mutual inductance is adaptable to the student laboratory. It has the advantages that neither the galvanometer constants nor the resistance of the galvanometer circuit need be known; that the galvanometer, being damped, can be read more accurately; and that the circuit is flexible and rapid in use.

By means of K (Fig. 1) the condenser is charged by being placed across the shunt R_2 containing the current I. It is then discharged through the galvanometer G and resistance R_1 in parallel, giving deflection D_1. Resistances R_1 and R_2 are chosen to give as large a deflection as possible. With K open, S is reversed, giving a deflection D_2. M is so chosen that D_1 and D_2 are approximately equal. If R_g is the combined resistance of G and the secondary of M, the quantity of electricity discharged by the condenser is $CR_2IR_1/(R_1+R_g)$, for it is proved in the original paper that, although the galvanometer circuit is inductive, the charge divides in inverse proportion to R_1 and R_g. The quantity passing upon reversal of S is $2MI/(R_1+R_g)$. Since D_1 and D_2 are proportional to these quantities, $C=(2M/R_1R_2)D_1/D_2$. In an actual case for a 1-μf condenser: M was 500μH; R_1, 500 ohms; R_2, 2 ohms; and D_1 and D_2, about 300 mm each. The accuracy was 0.1 percent.

When a fixed mutual inductance is used, the circuit is modified as in Fig. 2. If p is the reading of the potential divider (best obtained by interpolation from several settings) giving a condenser deflection equal to the deflection upon reversal of S, then $C=2M(P+R_2)/pR_1R_2$. —H. N. O.

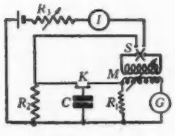


Fig. 1. Measurement of capacitance by ballistic method.

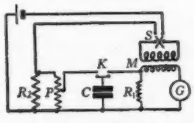


Fig. 2. Modified circuit with potential divider.

A working model to demonstrate the effect of heat on a confined volume of gas. D. G. Nicholson; *J. Chem. Ed.* **15**, 394, Aug., 1938. A working model illustrating the principle of Hero's engine for opening temple doors is shown in Fig. 1. One end of a piece of small, copper tubing is soldered into a hole in the bottom of the closed tin can A, and the other end is inserted into the rubber stopper of a bottle B partially filled with water. A glass tube extends from near the bottom of B to a position immediately above a beaker C, and a piece of gum rubber tubing, attached to the glass tube, extends into C. The beaker C is supported by a cord passing over a pulley P'. The doors D, D' have small, tin hinges which are soldered to two $\frac{1}{4}$-in. steel rods. The ends of the rods are tapered and are seated in bearings, consisting of solder poured into the holes in $\frac{1}{4}$-in. brass nuts, which have previously been fastened in position. Short pieces of iron wire are inserted in $\frac{1}{16}$-in. holes drilled in the steel rods. Cotton cord is fastened to the ends of the iron wires and passes over the pulleys to the beaker C and to the counterweight W. When some alcohol-soaked cord is ignited on the top of the can A (the "altar"), the air in the latter expands and forces water from B into C. When the counterweight W is overbalanced, C descends and opens the doors. Extinguishing the flame reverses the process and the doors shut. A "hooded" strip of copper soldered to the side of can A speeds up the expansion. Some trial is required to obtain the proper sized counterweight W.—D. R.

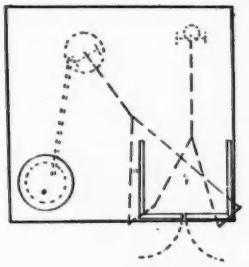
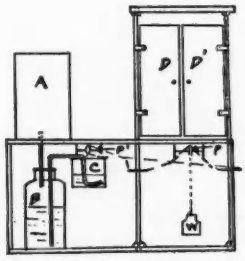


Fig. 1. Model of Hero's engine.



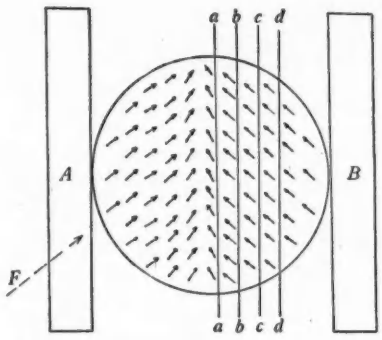


FIG. 1. Model to illustrate ferromagnetism.

A model to illustrate ferromagnetism. L. F. BATES; *J. Sci. Inst.* **15**, 237, July, 1938. A Ewing model consisting of a series of pivoted compass needles may be modified to illustrate the sudden turning of elementary magnets from one crystal direction to another, as required by modern concepts of ferromagnetism, when an iron crystal is magnetized along any direction other than the 100. [See Bozorth and Dillinger, Am. Phys. Teacher **5**, 157 (1937).] In one form 89 tiny magnets are mounted as in Fig. 1, in a circular glass case, diameter 4.5 in., between two rectangular coils *A* and *B* of 50 turns each. Four copper wires *aa*, *bb*, *cc*, *dd* in parallel are mounted below the needles and a permanent magnet a short distance away gives a field in the direction of *F*. A total current of 2 amp in the wires causes the needles to set approximately as shown, representing two domains in a ferromagnetic crystal with their electron spins aligned parallel to adjacent sides of a crystal.

To illustrate magnetism processes, a current varying from 0 to 0.5 amp is supplied to *A* and *B* to produce clockwise rotation of the needles. When the needles along the boundary of the two domains show signs of change, corresponding to a growth of one domain at the expense of the other, the current in *aa*, etc, is reversed and the magnets on the right turn through 90°. This corresponds to change in magnetization direction of this domain from one crystal direction to another more closely aligned with the applied field. As the current in *A* and *B* is gradually increased to 5 amp, all needles turn and finally set with axes parallel to the axis of *A* and *B*, corresponding to gradual rotation of domain magnetization into coincidence with the applied field. The needle system may easily be projected on a screen.—H. N. O.

THE LAG IN THE SOCIAL STUDIES

Why the social sciences lag behind the physical and biological sciences. J. MAYER; *Sci. Mo.* **46**, 564–6, June, 1938. Compared with the marvelous advances of physics and chemistry, and the rapid strides made in the past century by geology and biology, there apparently has been little, if any, real progress in an understanding of human relations and in the solution of problems such as war, minority protection, unemployment, maldistribution of wealth and income, or depression. To clarify the reasons for this sluggish progress in the social studies, one may profitably trace the history of the sciences. A definite sequence of development is indicated, from the most abstract understanding of nature to the more concrete problems which we designate as human or social.

Mathematics seems to have been the only science that the ancient Greeks succeeded in establishing on a fairly secure basis; although they assembled considerable materials in astronomy, physics, geology, and biology, knowledge was then so meager in these fields that in most of them they handed down to their successors about as much misconception as accurate information. Not until 1600 did astronomy shake off the misconceptions that had prevented its constructive advance; yet, without some of the mathematical developments of the Greeks, Kepler would have been unable to formulate his laws of planetary motion. The work of Galileo and Newton followed, and by 1700 physics was well along the road to discarding past misconceptions and to building a secure foundation. Another century passed before chemistry, aided by certain developments in physics, found a secure basis for its establishment; and by the third of the next century, the ground work had been laid for the extraordinary advances in organic and inorganic chemistry that followed.

Until physics and chemistry were well enough along in the development of principles and of such tools as the microscope, the balance, and the thermometer, it was impossible for geology and biology to find sufficient root for their modern advance. It was not until 1830 that gross geological misconceptions were being swept away and that Lyell was laying the foundations of geology. Not until about 1860 were the three great generalizations developed that laid securely the foundations of modern biology; namely, the discovery of the cell and protoplasm, the discovery of the germ layers, and the enunciation of the evolutionary hypothesis.

To understand anything clearly about psychology was hardly possible until we had that part of biology dealing with the structure of the sense organs, the tracing of the nervous system, and, especially, the analysis of the functions of the spinal cord and brain—a development that came only in the last half of the nineteenth century.

To understand social relations, there must be a sound understanding, first, of the human environment, which is the task of most of the sciences we have outlined, and, second, of the biological and psychological limitations of man himself. This was impossible until biology and psychology were far enough along the road of modern scientific development. Only now, in fact, is any satisfactory understanding of social phenomena becoming possible. There still exists in the social studies any number of misconceptions, carried down to us from the medieval period, particularly, which must be swept away before real progress is possible. We may not even now be ready for this rapid advance; but, in the light of the history of the sciences, we can at least understand why there is so much hesitation and misunderstanding in contemporary efforts to solve social problems. Only as we reach down into all the sciences and utilize them for the task ahead, can we hope some day to have as clear an understanding in economics, government, and sociology as we have long since secured in the physical and biological sciences.—D. R.